US009201172B2

(12) **United States Patent**
Fujii et al.

(10) **Patent No.: US 9,201,172 B2**
(45) **Date of Patent: Dec. 1, 2015**

(54) **ANTI-REFLECTION COATING, OPTICAL MEMBER HAVING IT, AND OPTICAL EQUIPMENT COMPRISING SUCH OPTICAL MEMBER**

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(73) Assignee: **RICOH IMAGING COMPANY, LTD.**, Tokyo (JP)

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(21) Appl. No.: **14/019,901**

(22) Filed: **Sep. 6, 2013**

(65) **Prior Publication Data**

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(30) **Foreign Application Priority Data**

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Dec. 11, 2012 (JP) 2012-270750
Jul. 19, 2013 (JP) 2013-151037

(51) **Int. Cl.**
G02B 27/00 (2006.01)
G02B 1/11 (2015.01)
G02B 1/115 (2015.01)

(52) **U.S. Cl.**
CPC . ***G02B 1/11*** (2013.01); ***G02B 1/115*** (2013.01)

(58) **Field of Classification Search**
CPC G02B 1/11; G02B 1/15; G02B 1/111
USPC 359/601, 586–589, 577, 615; 351/163, 351/166, 177
See application file for complete search history.

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JP 2005-055569 3/2005
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Primary Examiner — Scott J Sugarman
Assistant Examiner — Mustak Choudhury
(74) *Attorney, Agent, or Firm* — Greenblum & Bernstein, P.L.C.

(57) **ABSTRACT**

A anti-reflection coating comprising first to ninth layers laminated in this order on a substrate for having reflectance of 0.2% or less to light in a visible wavelength range of 390-720 nm, the second, fourth, sixth and eighth layers being high-refractive-index layers formed by high-refractive-index materials having refractive indices of 2.21-2.70 to a helium d-line having a wavelength of 587.56 nm; the first, third, fifth and seventh layers being intermediate-refractive-index layers formed by an intermediate-refractive-index material having a refractive index of 1.40 or more and less than 1.55 to the d-line; and the ninth layer being a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.35 or more and less than 1.40 to the d-line.

15 Claims, 44 Drawing Sheets

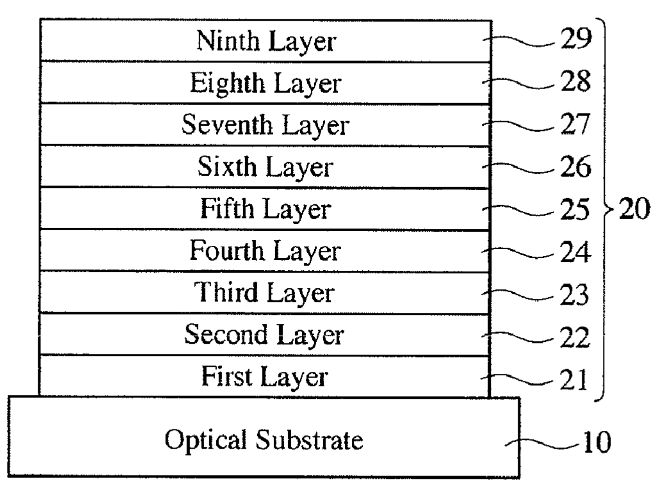


Fig. 1

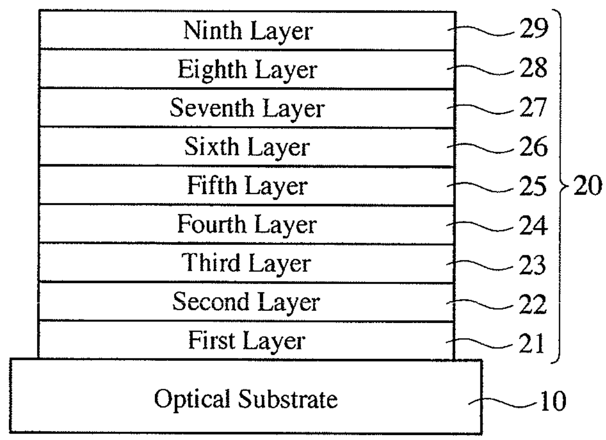

Ninth Layer
29
Eighth Layer
28
Seventh Layer
27
Sixth Layer
26
Fifth Layer
25
20
Fourth Layer
24
Third Layer
23
Second Layer
22
First Layer
21
Optical Substrate
10

Fig. 2

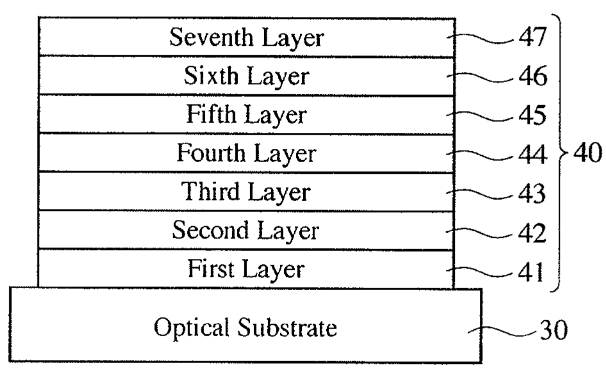
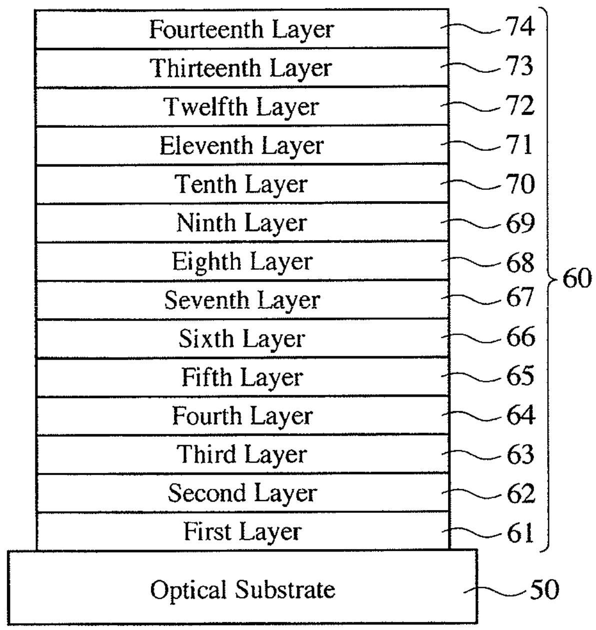
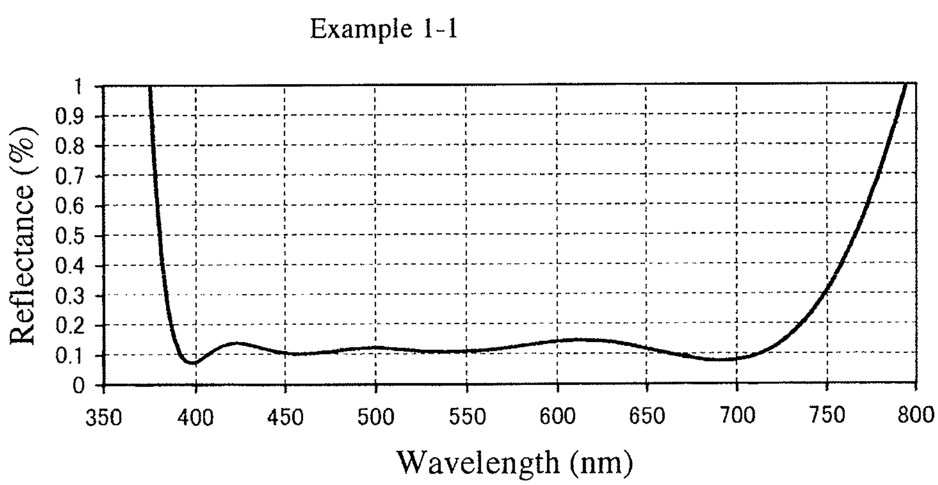

Seventh Layer
47
Sixth Layer
46
Fifth Layer
45
Fourth Layer
44
40
Third Layer
43
Second Layer
42
First Layer
41
Optical Substrate
30

Fig. 3



Fourteenth Layer
74
Thirteenth Layer
73
Twelfth Layer
72
Eleventh Layer
71
Tenth Layer
70
Ninth Layer
69
Eighth Layer
68
Seventh Layer
67
Sixth Layer
66
Fifth Layer
65
Fourth Layer
64
Third Layer
63
Second Layer
62
First Layer
61
60
Optical Substrate
50

Fig. 4



Example 1-1
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 5

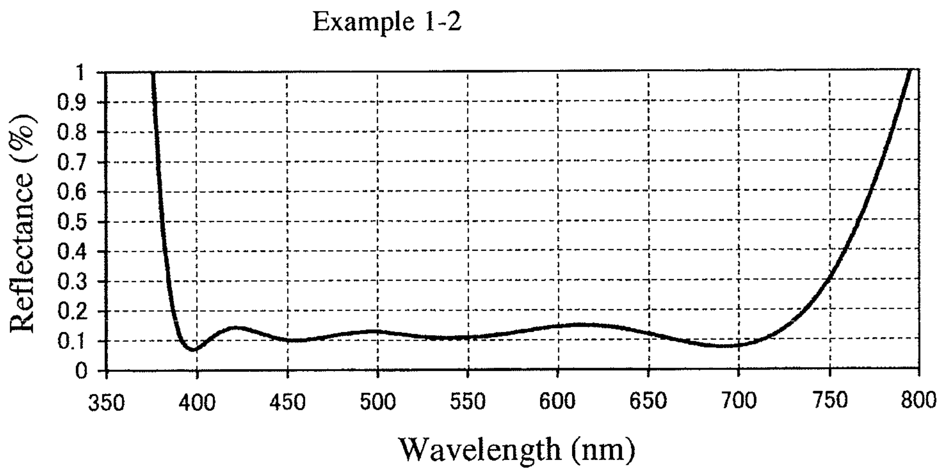

Example 1-2
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 6

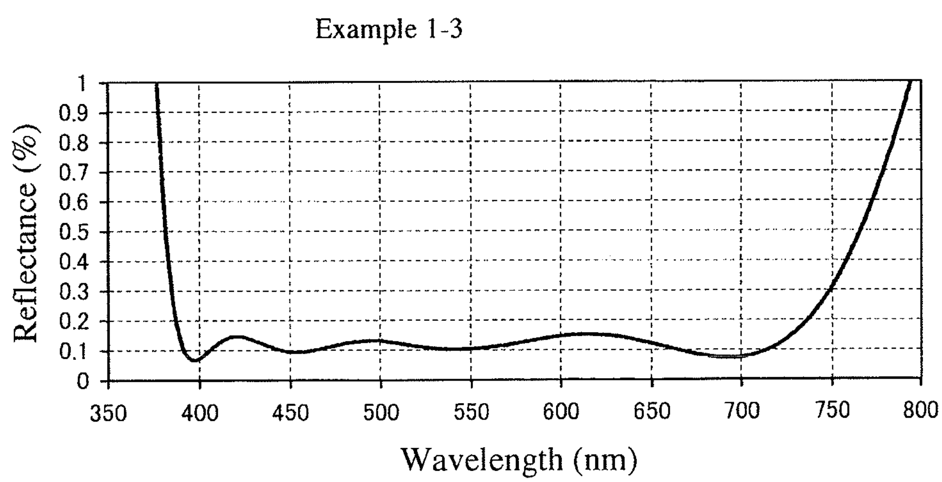

Example 1-3
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 7

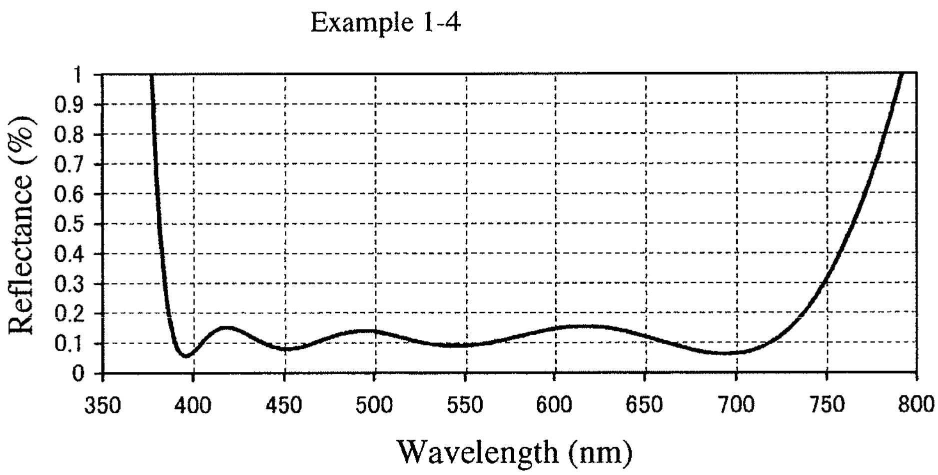

Example 1-4
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 8

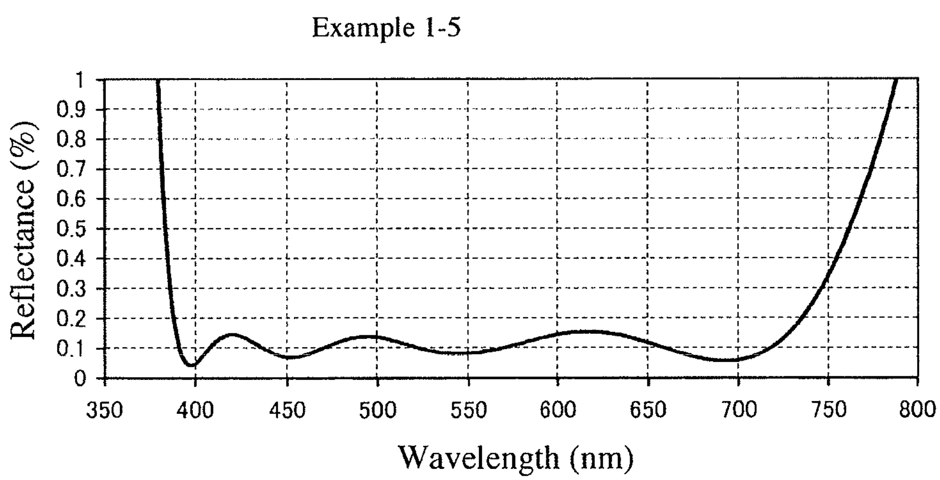

Example 1-5
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 9

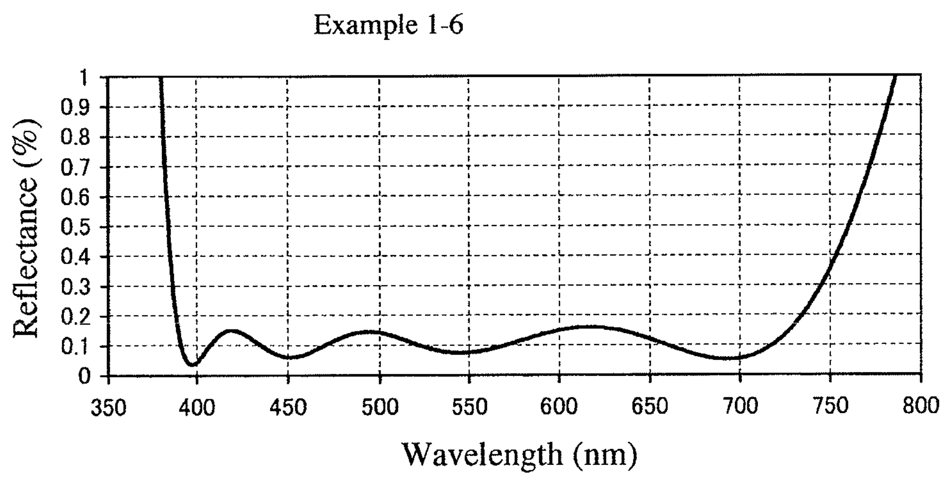

Example 1-6
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 10

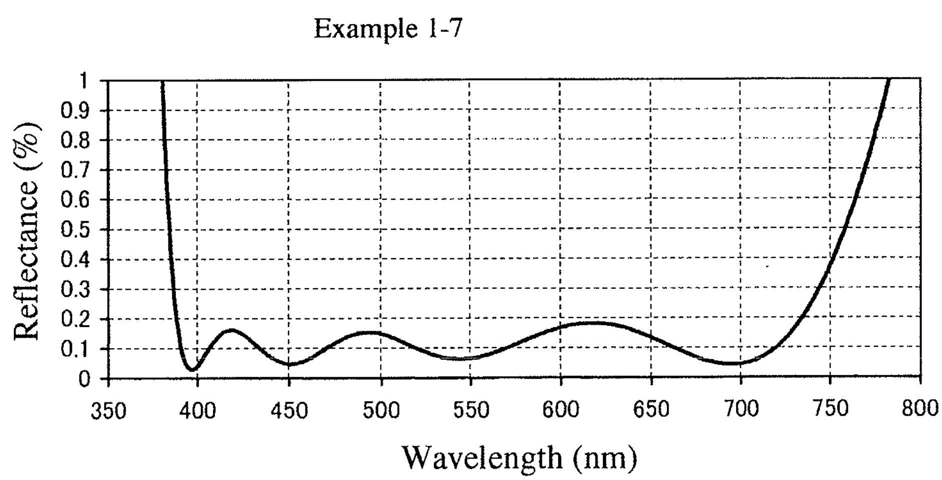

Example 1-7
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 11

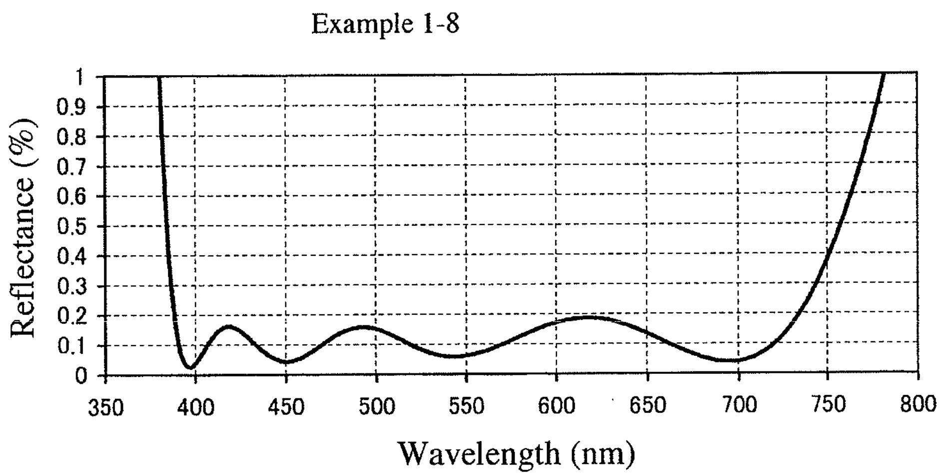

Example 1-8
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 12

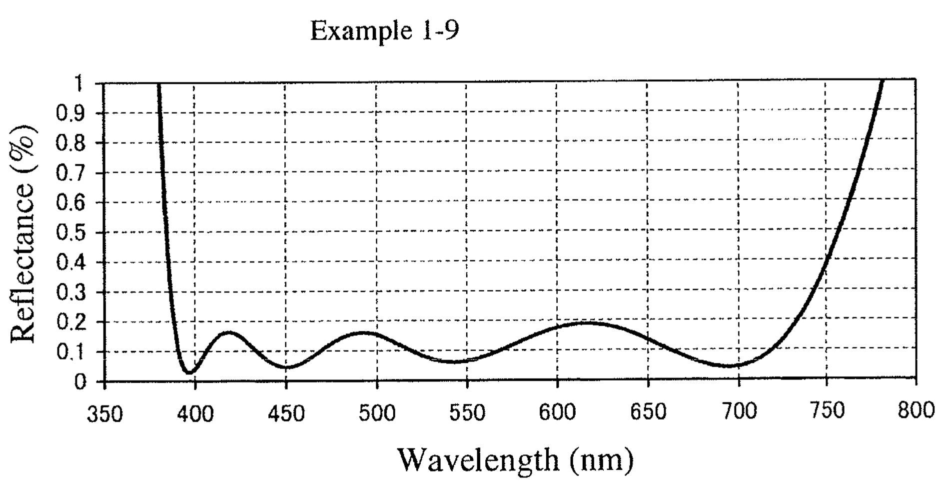
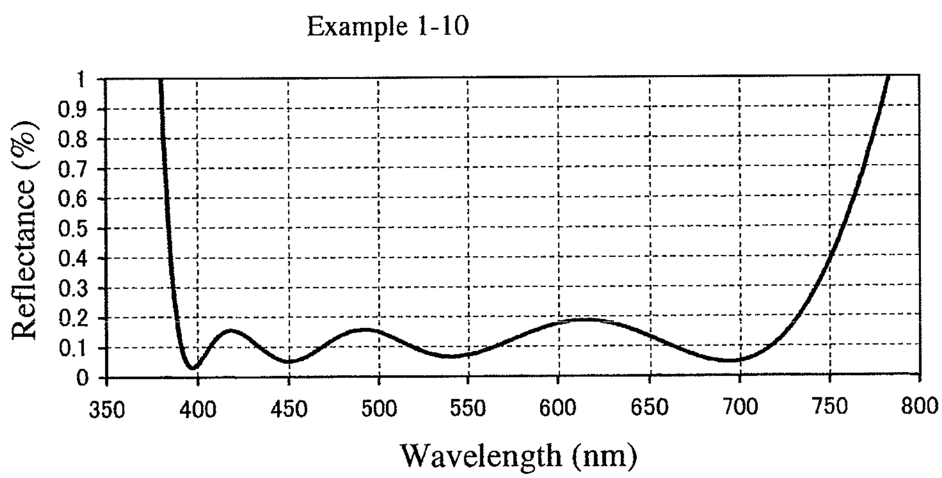

Example 1-9
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 13


Example 1-10
Reflectance (%)
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0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 14

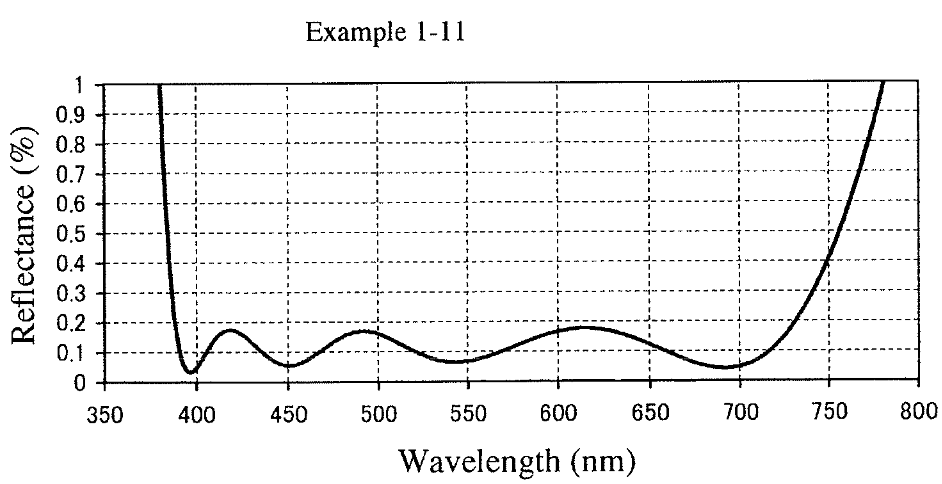

Example 1-11
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 15

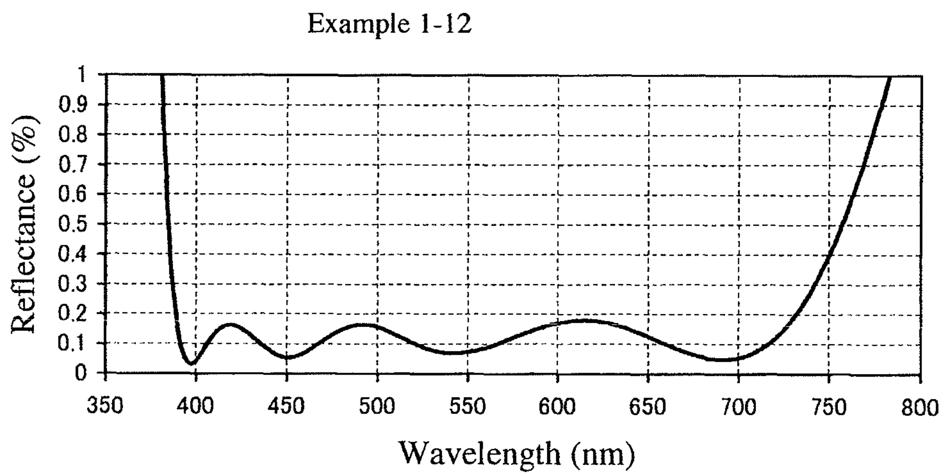

Example 1-12
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 16

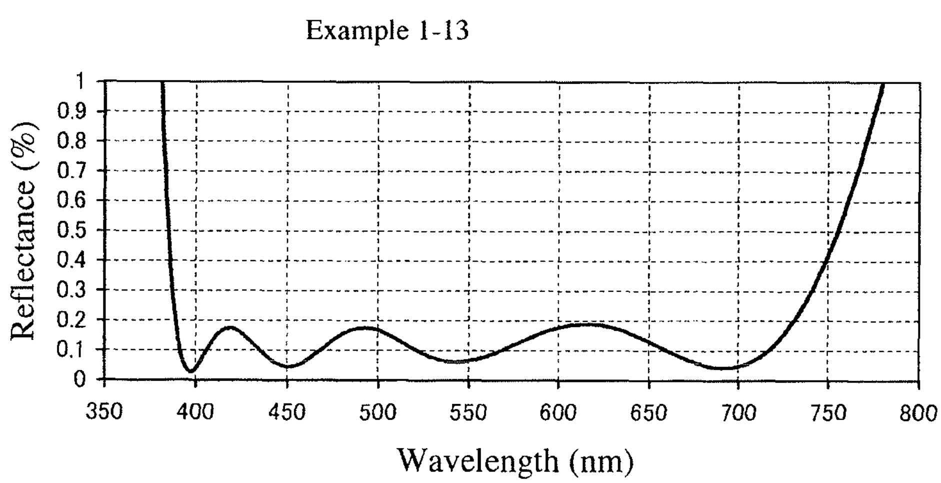

Example 1-13
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 17

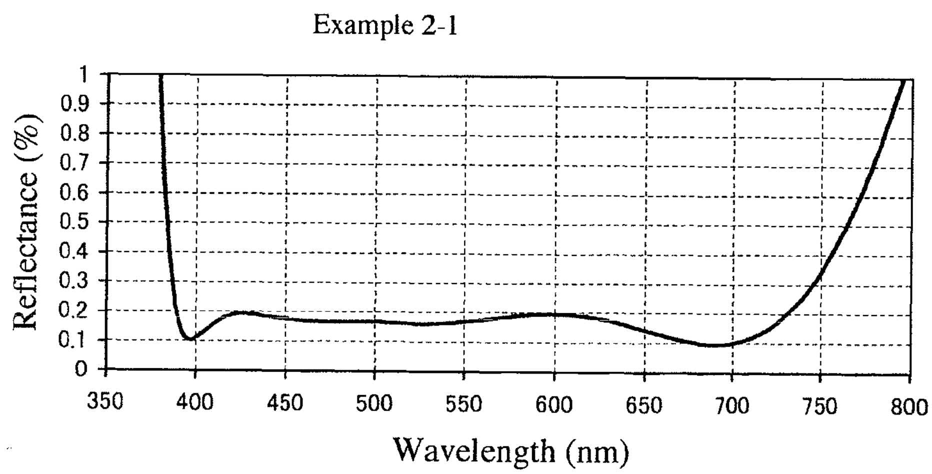

Example 2-1
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 18

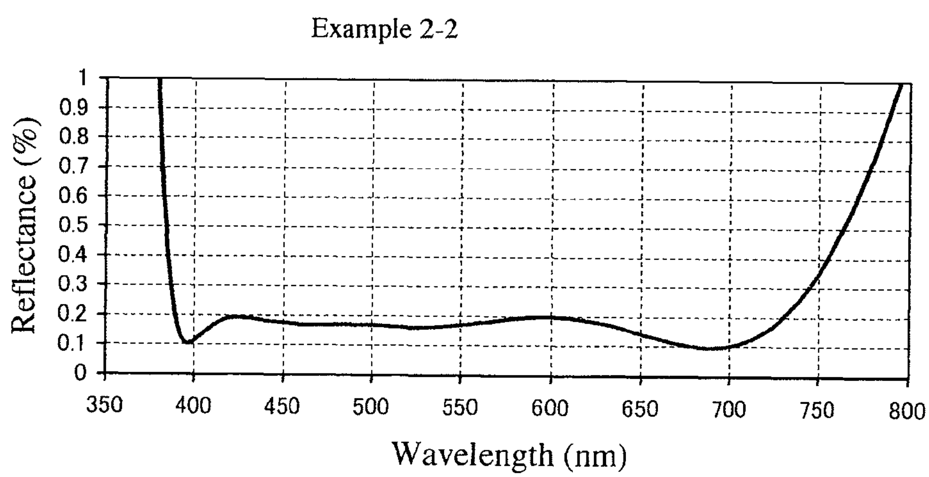

Example 2-2
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 19

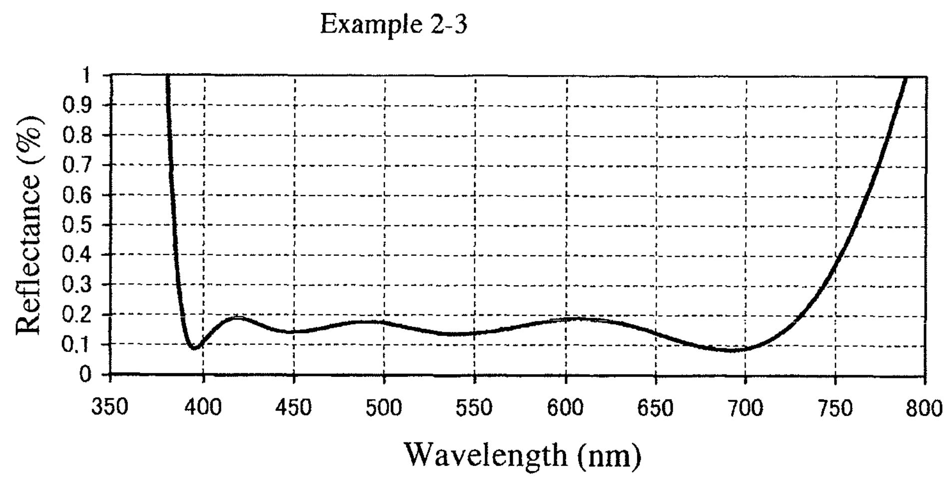

Example 2-3
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 20

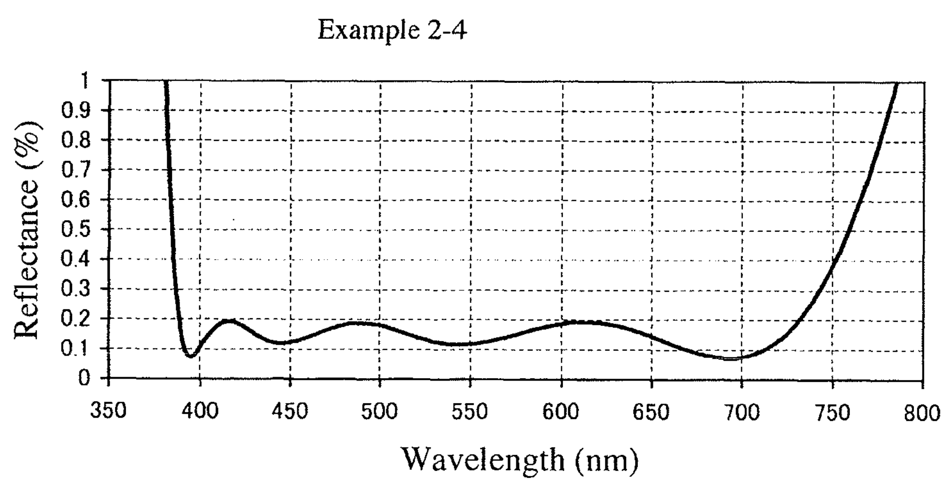

Example 2-4
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 21

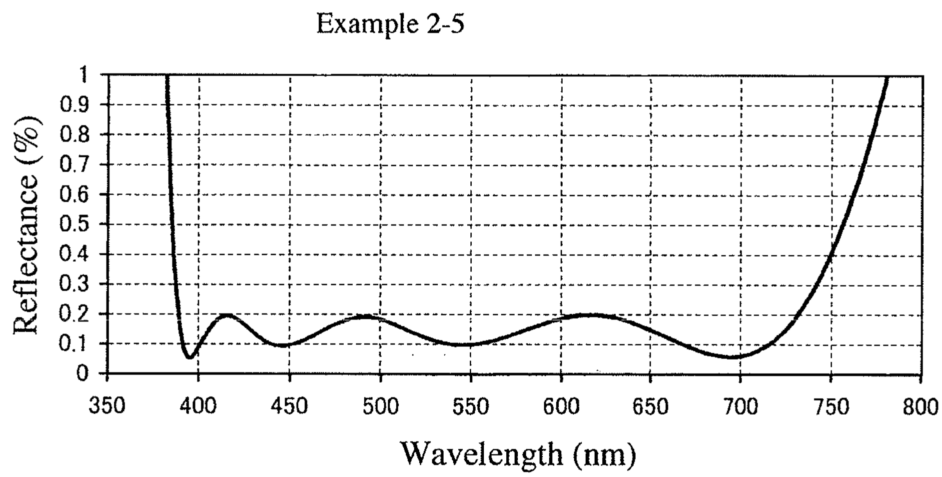

Example 2-5
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 22

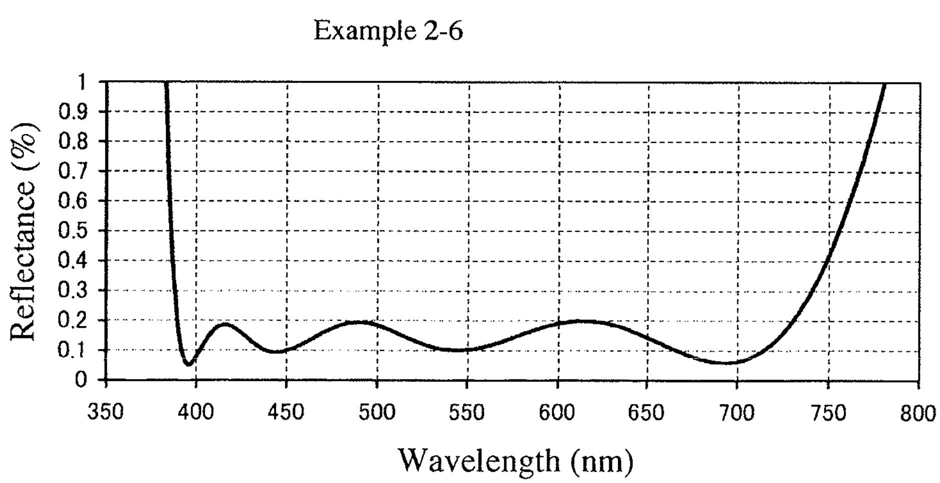

Example 2-6
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 23

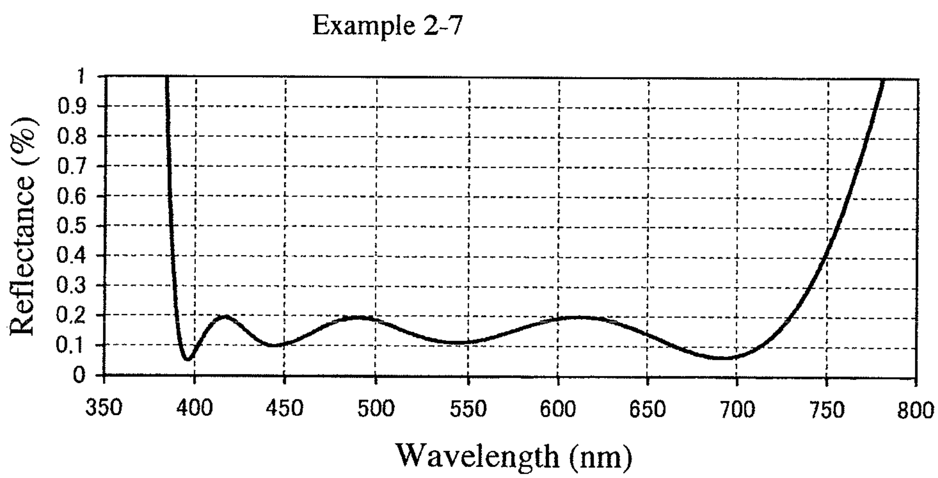

Example 2-7
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 24

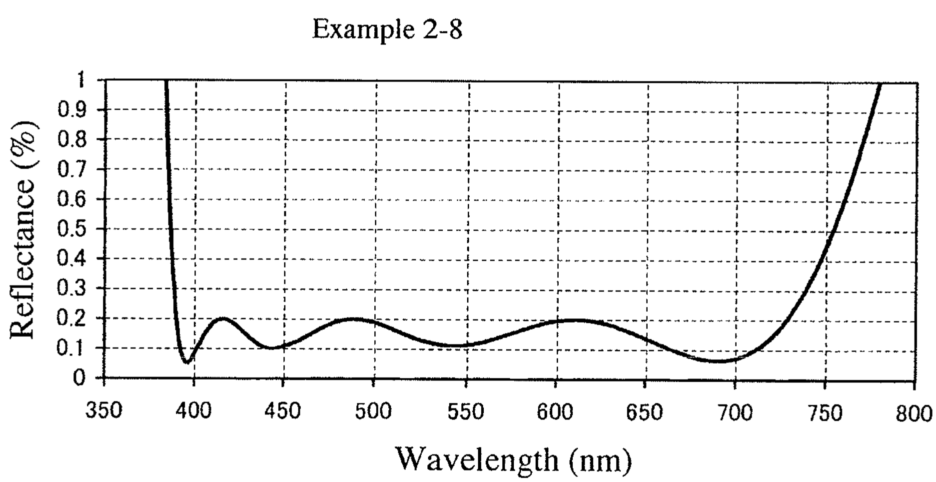

Example 2-8
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 25

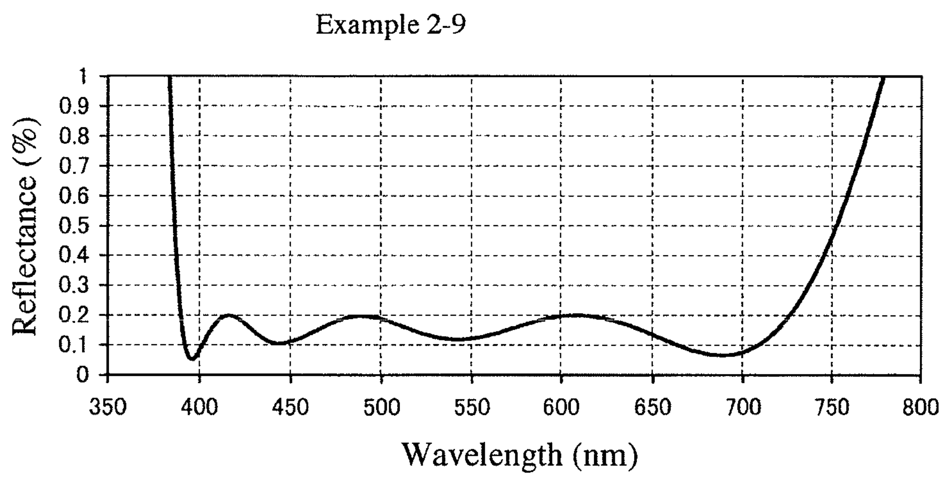

Example 2-9
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350 400 450 500 550 600 650 700 750 800
Wavelength (nm)

Fig. 26

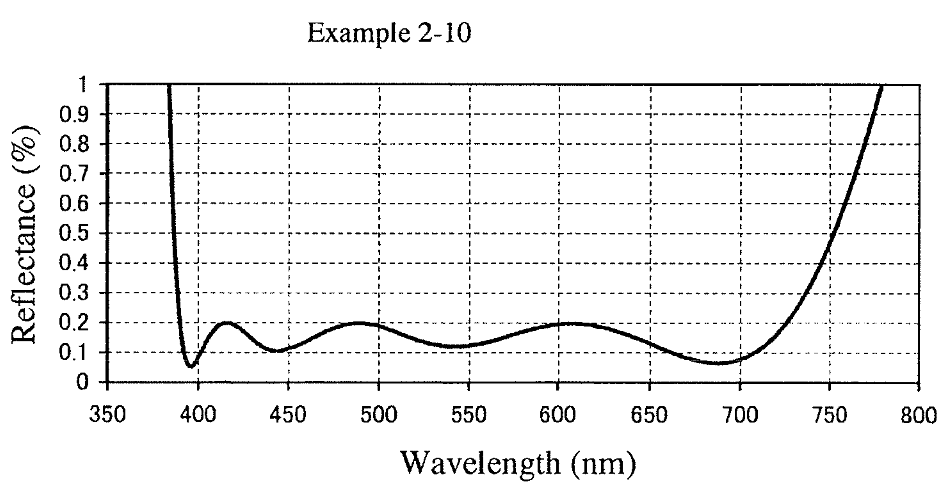

Example 2-10
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350 400 450 500 550 600 650 700 750 800
Wavelength (nm)

Fig. 27

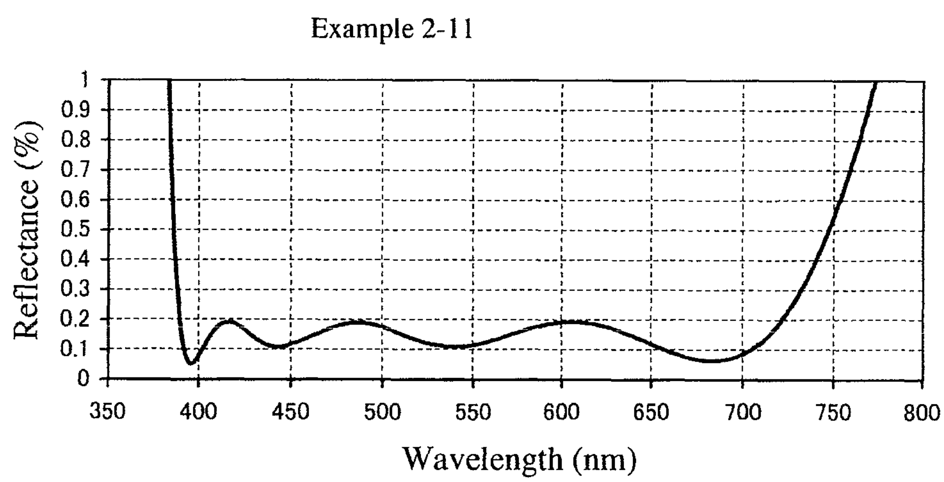

Example 2-11
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 28

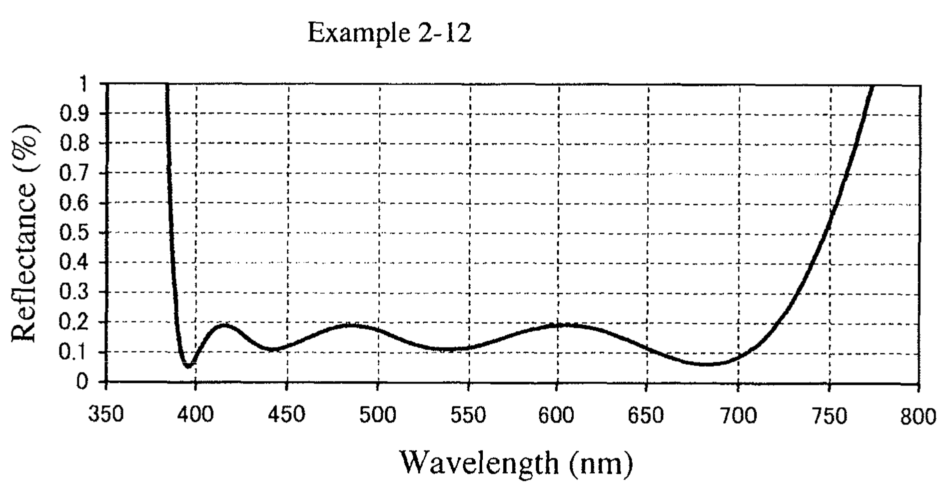

Example 2-12
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 29

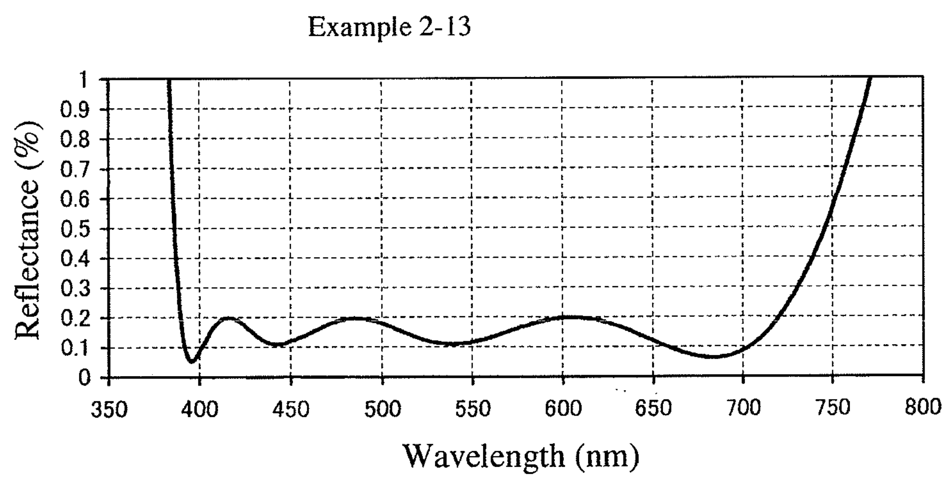

Example 2-13
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 30

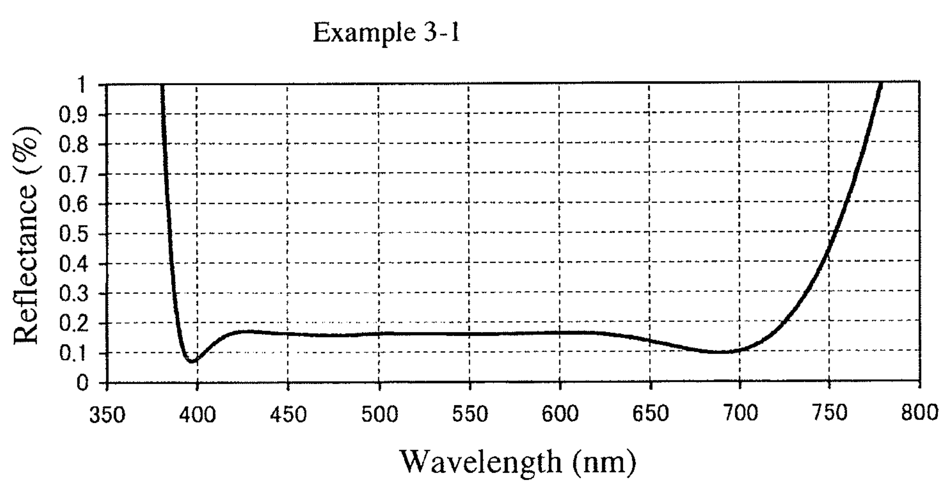

Example 3-1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 31

Example 3-2

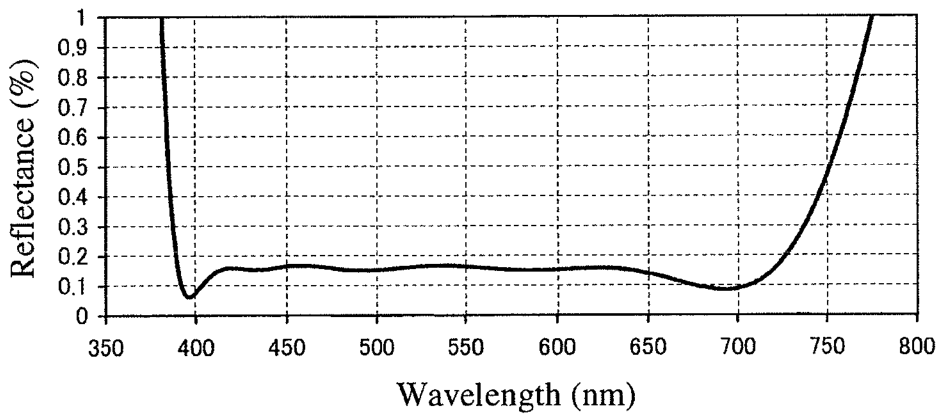


Fig. 32

Example 3-3

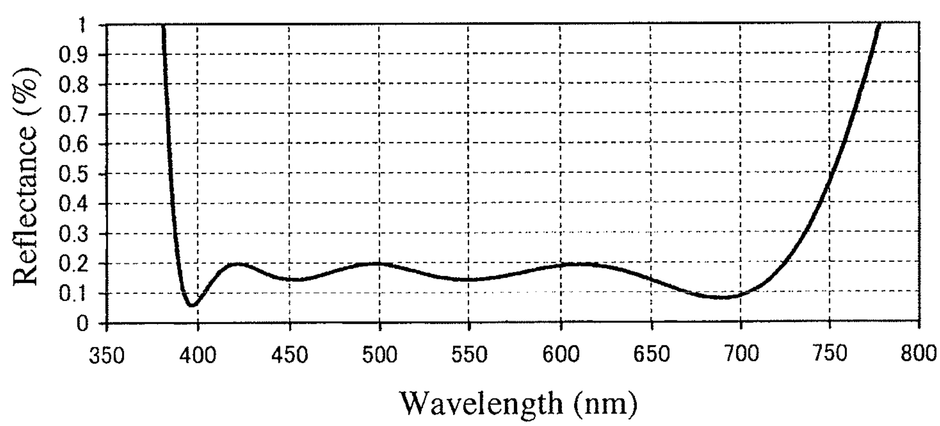


Fig. 33

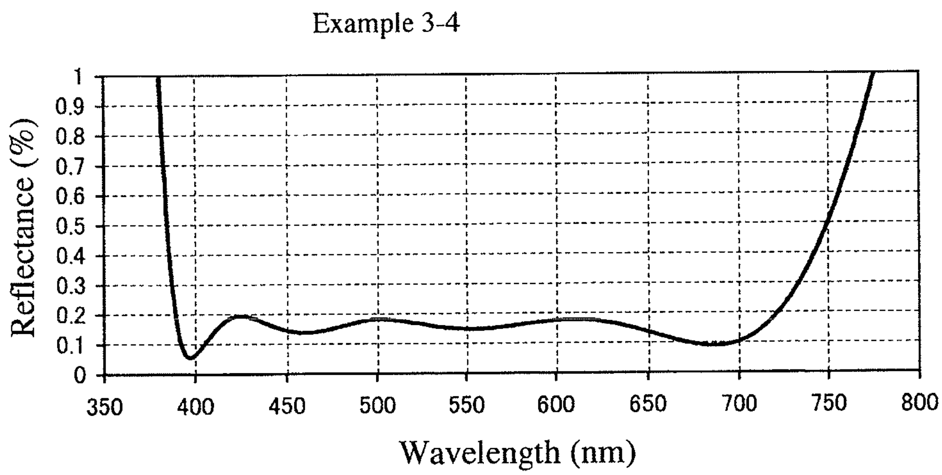

Example 3-4
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 34

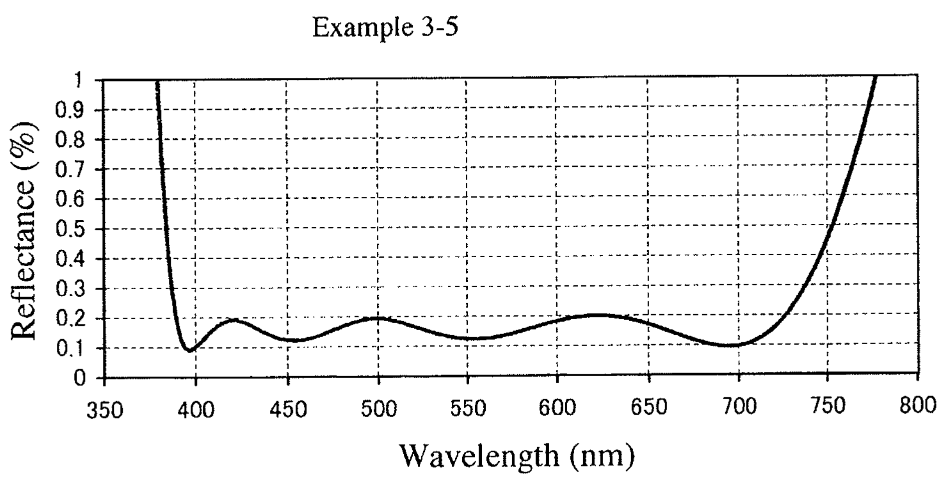

Example 3-5
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 35

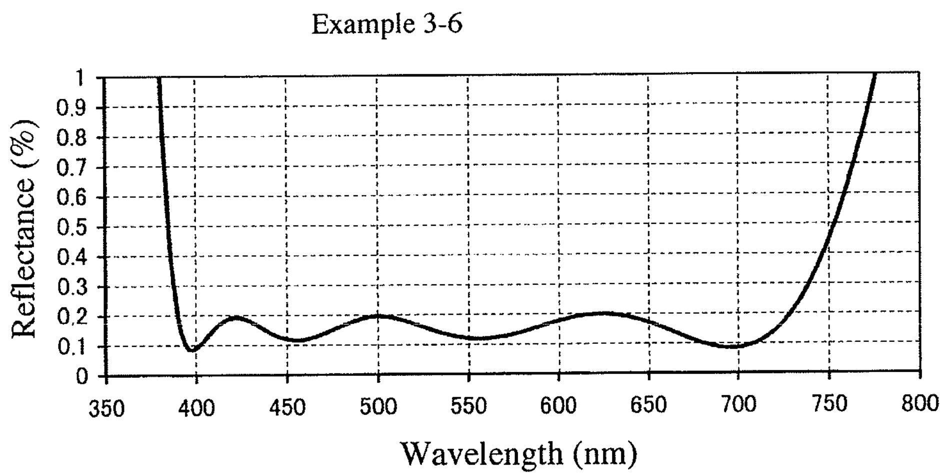

Example 3-6
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 36

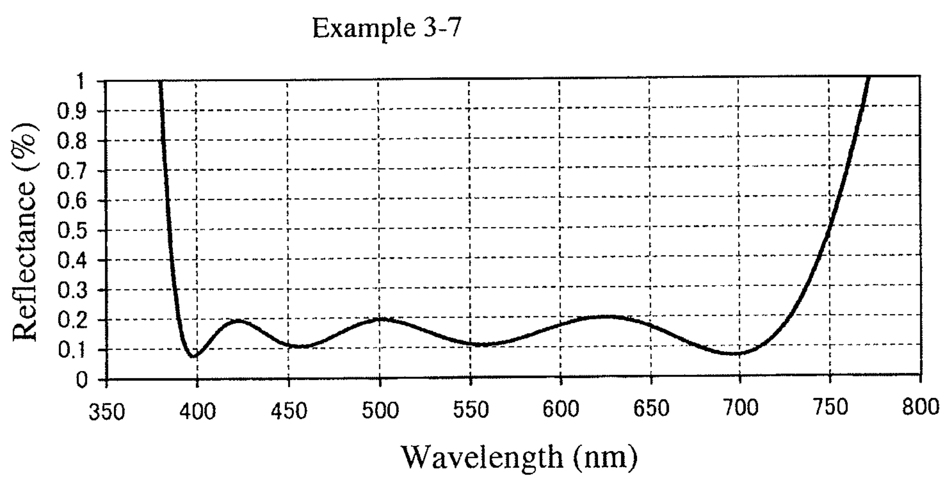

Example 3-7
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 37

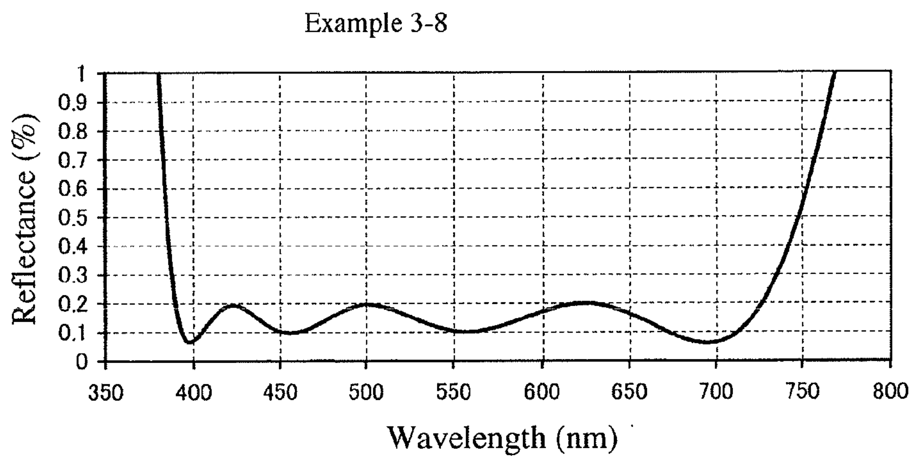

Example 3-8
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 38

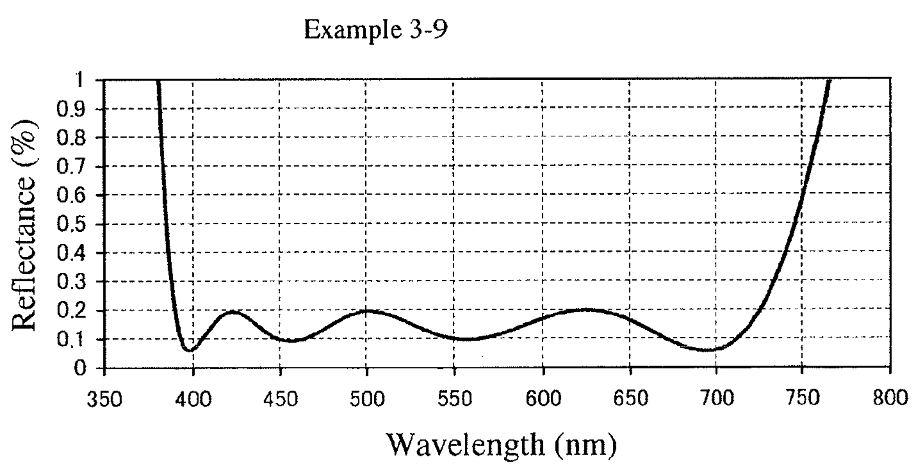

Example 3-9
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 39

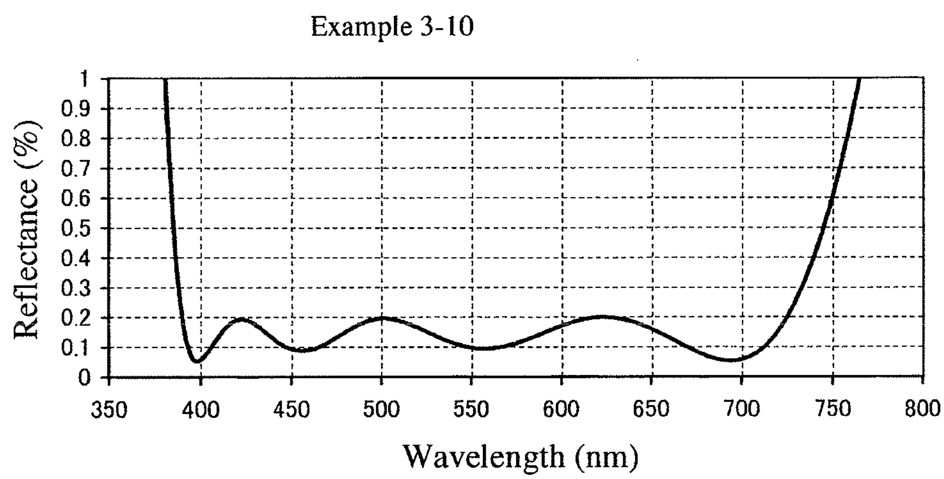

Example 3-10
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 40

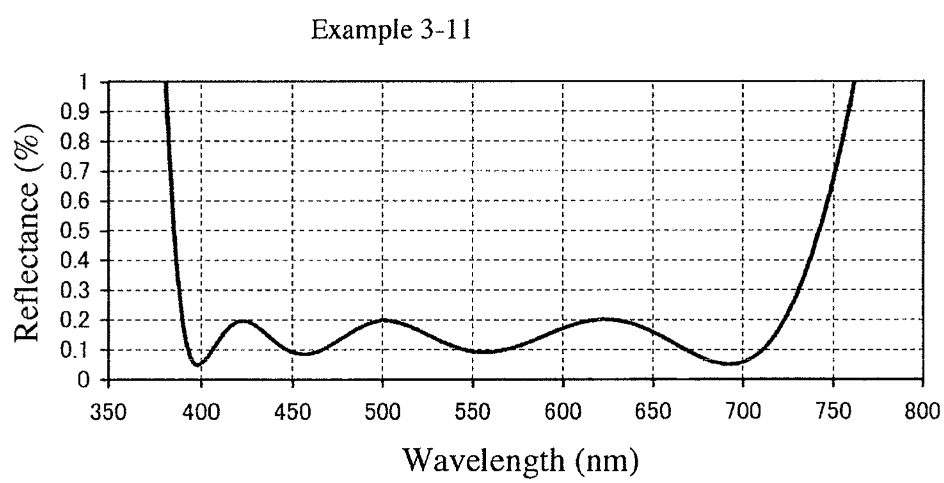

Example 3-11
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 41

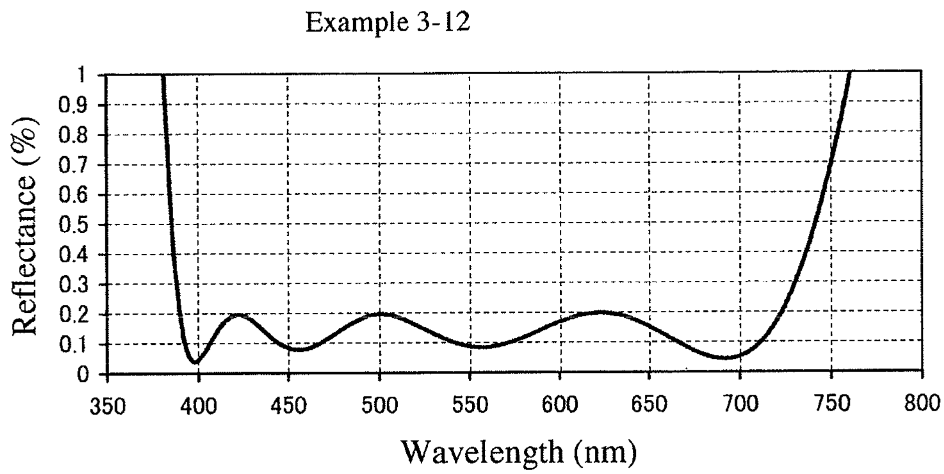

Example 3-12
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 42

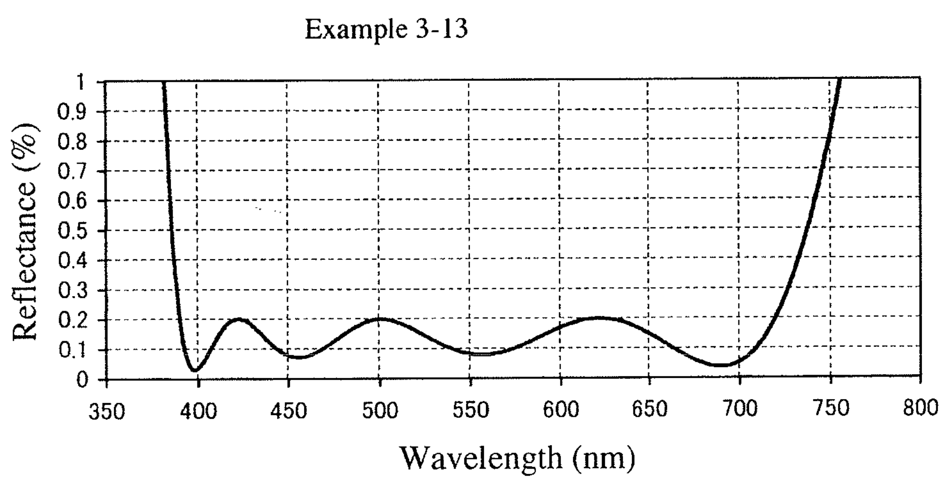

Example 3-13
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 43

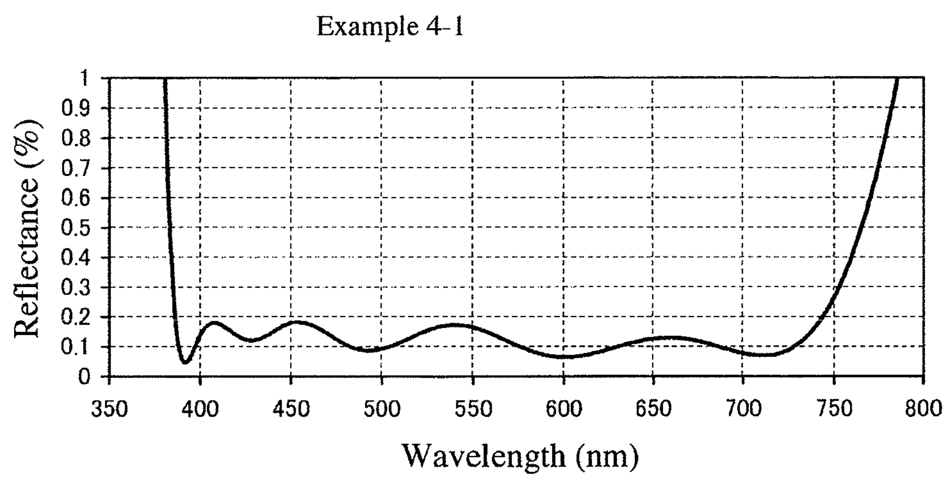

Example 4-1
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 44

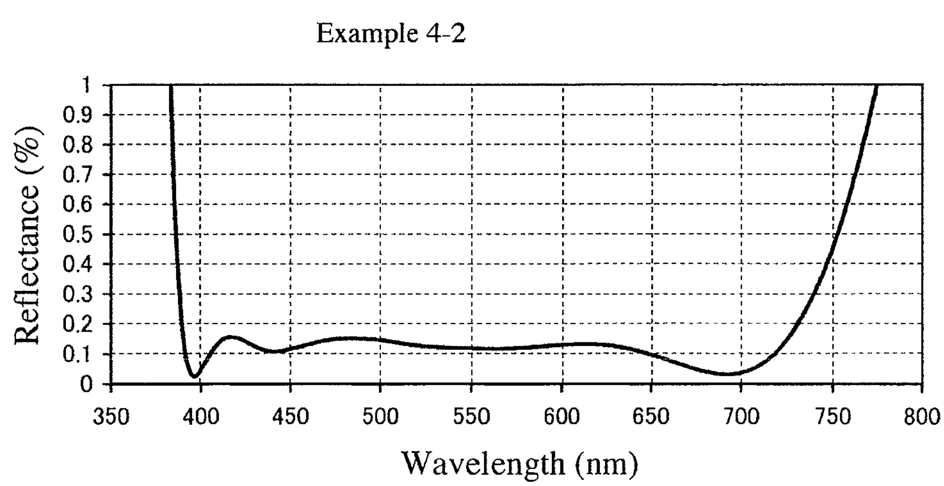
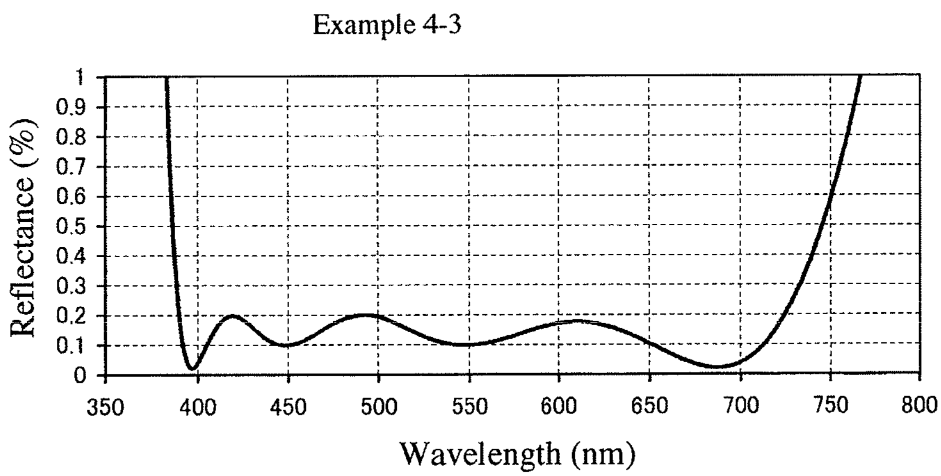
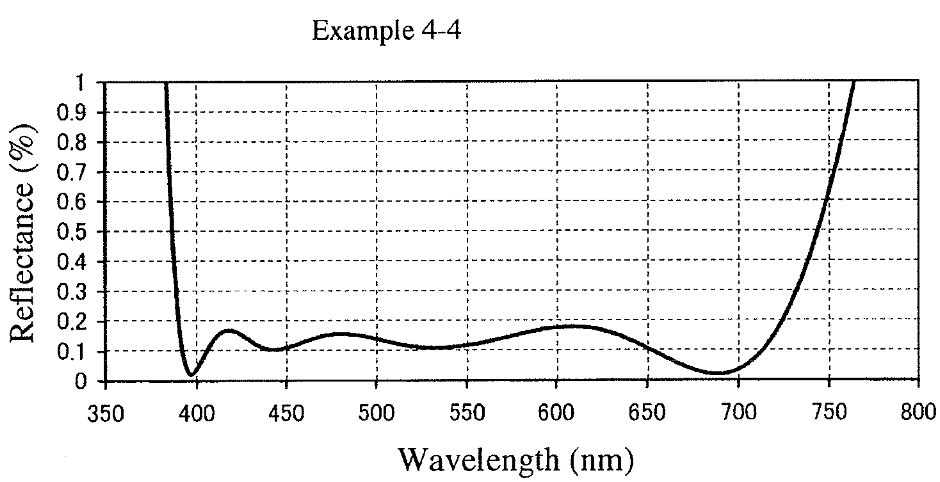

Example 4-2
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 45



Example 4-3
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 46



Example 4-4
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 47

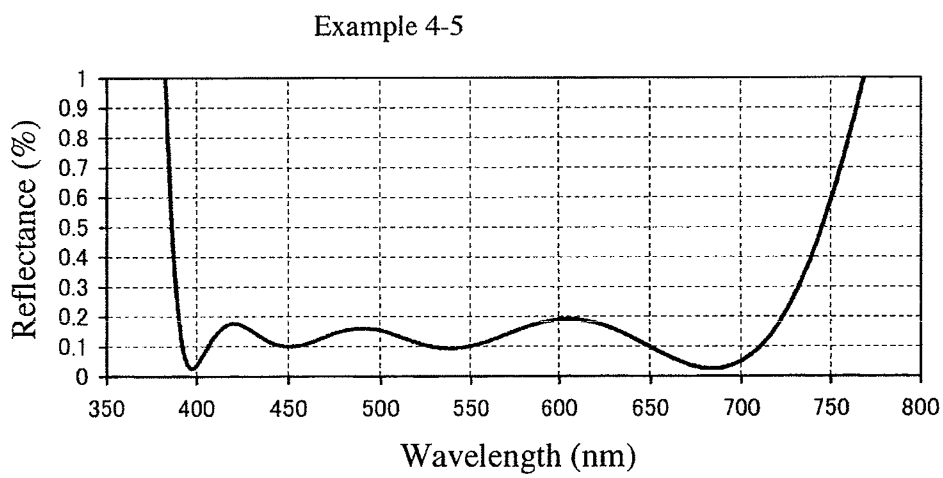

Example 4-5
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 48

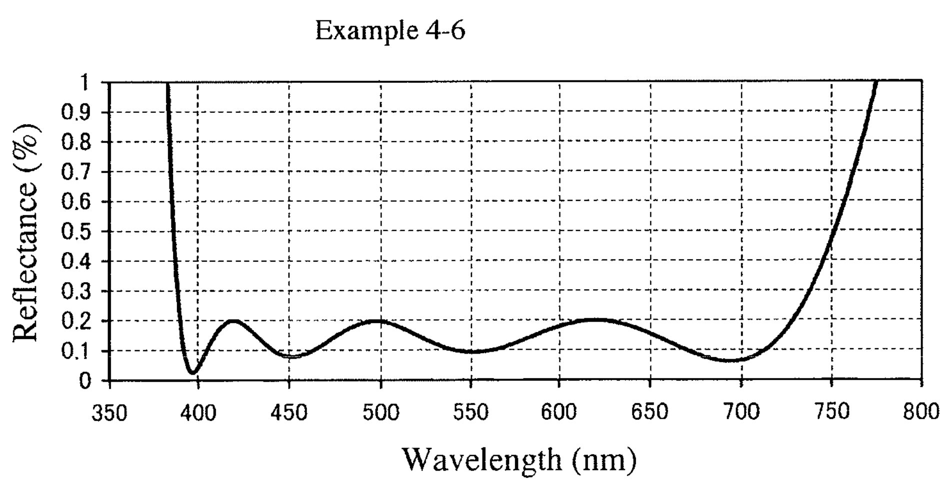

Example 4-6
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 49

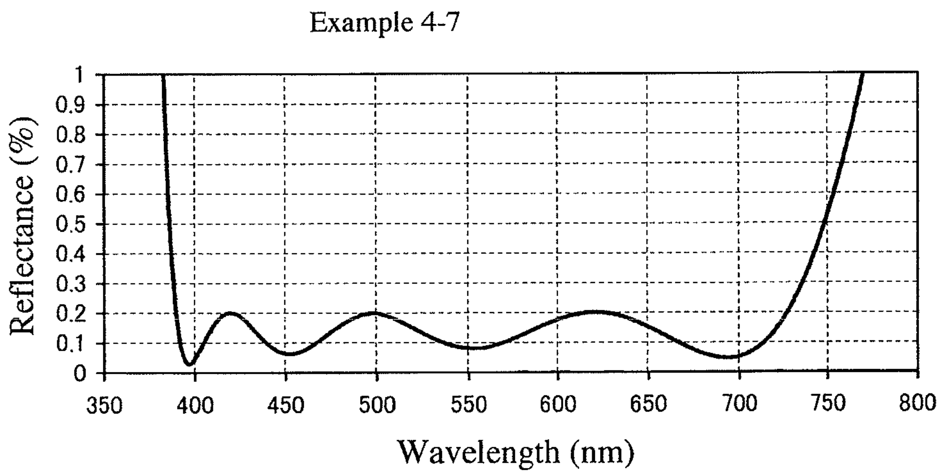

Example 4-7
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 50

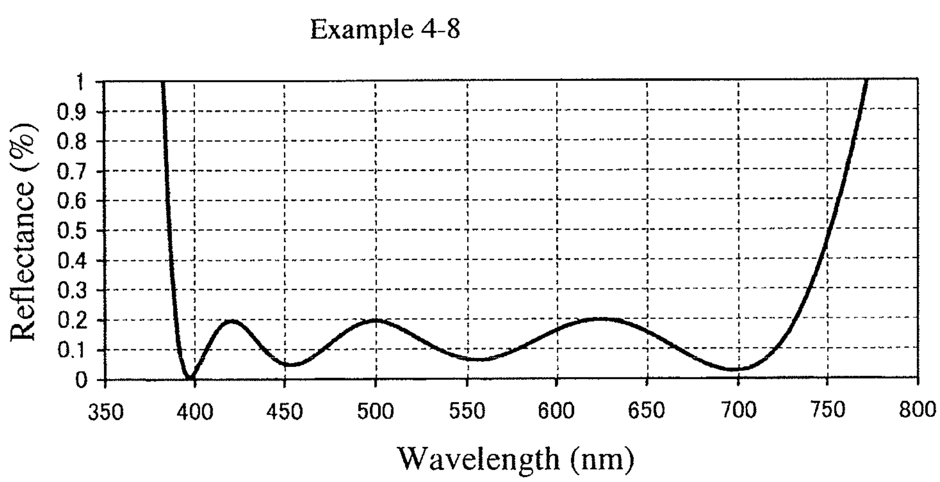

Example 4-8
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 51

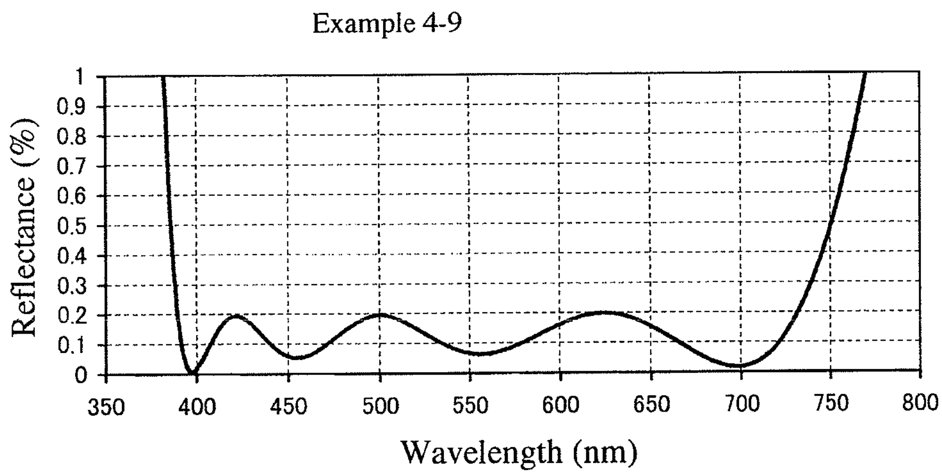

Example 4-9
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 52

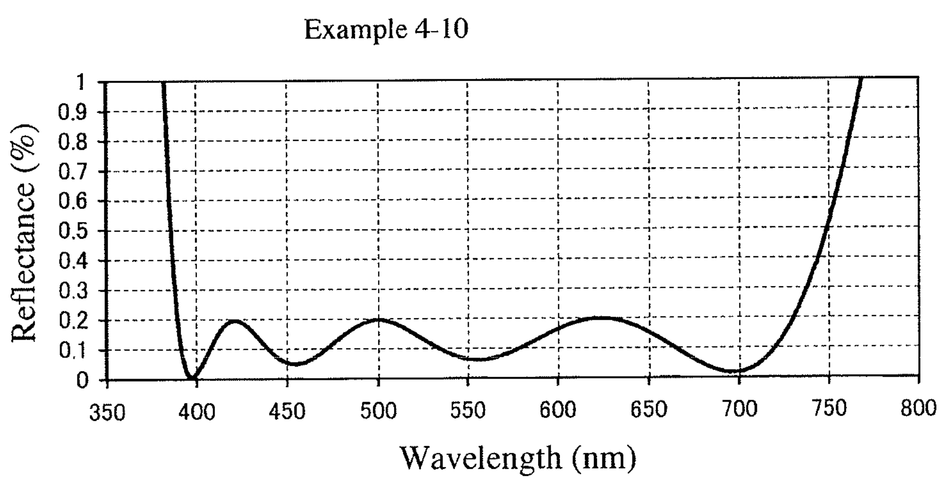

Example 4-10
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 53

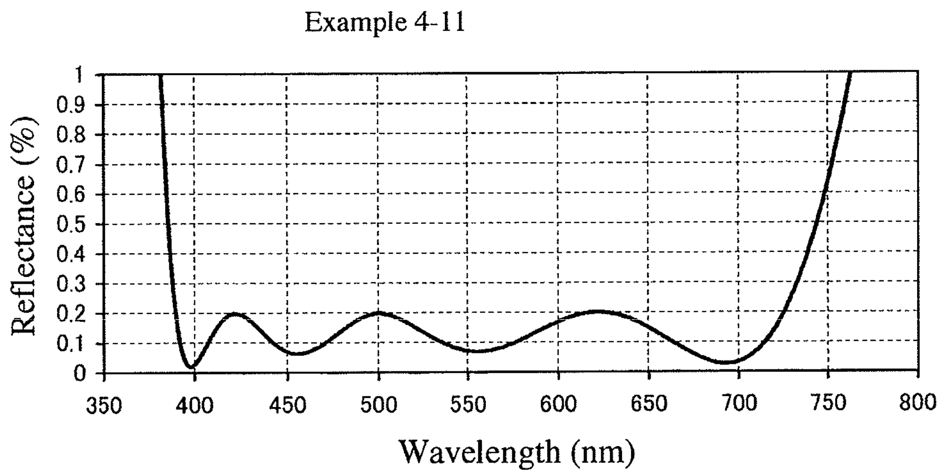

Example 4-11
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 54

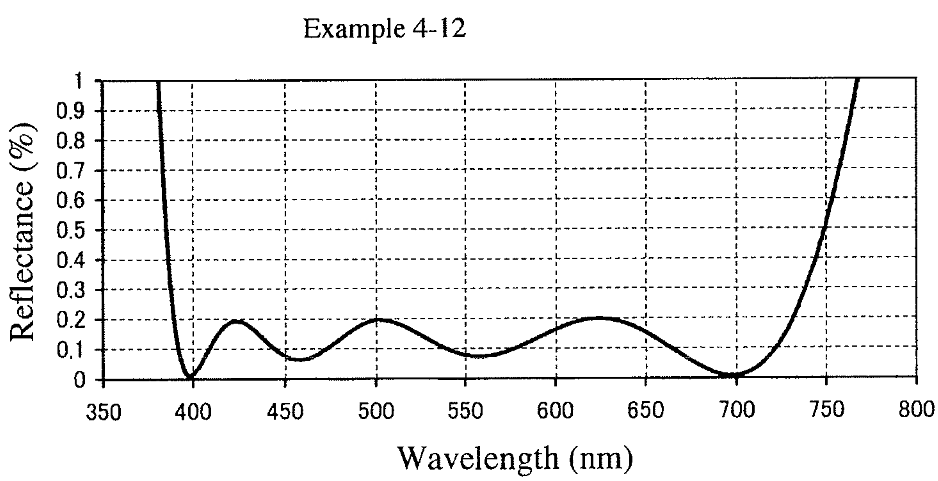

Example 4-12
Reflectance (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 55

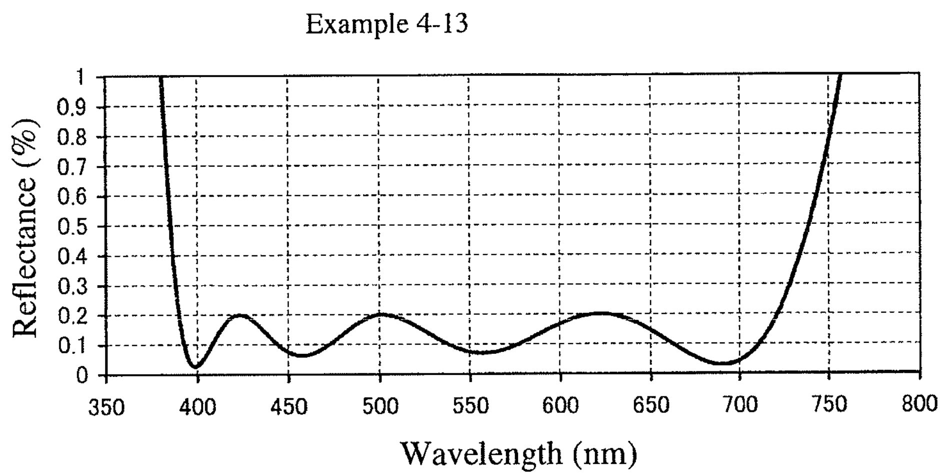

Example 4-13
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 56

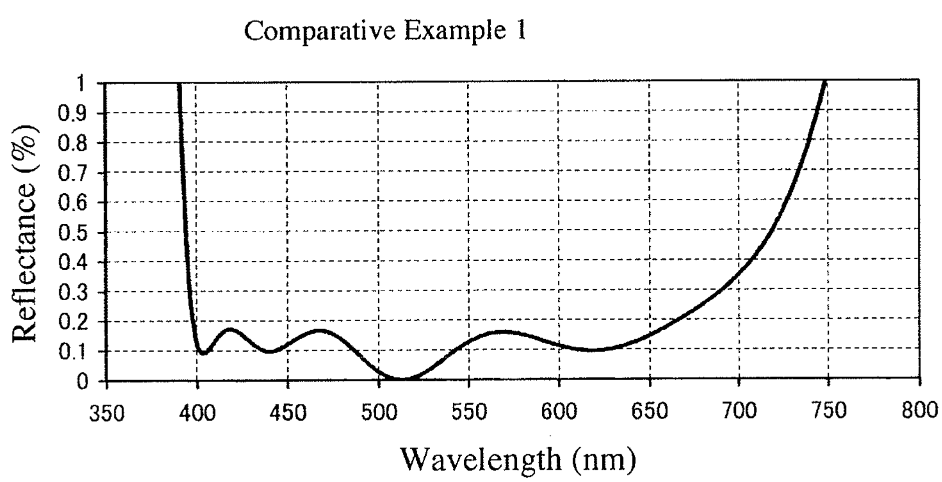

Comparative Example 1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Fig. 57

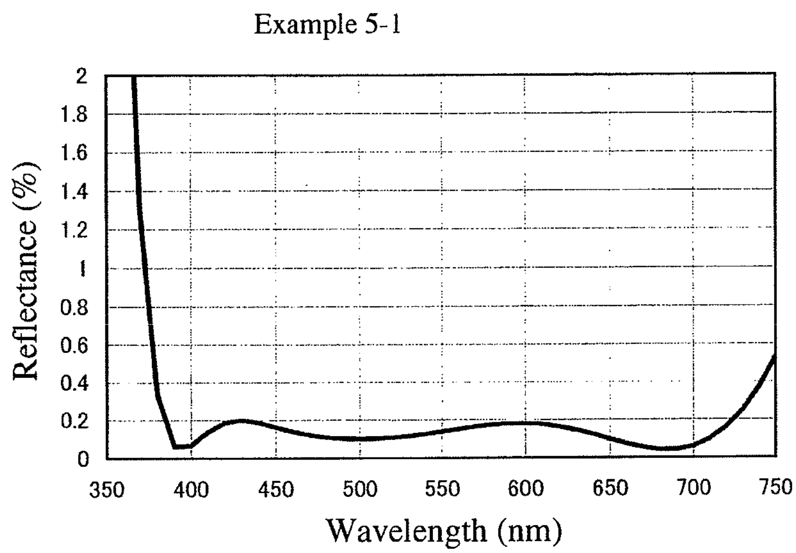

Example 5-1
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 58

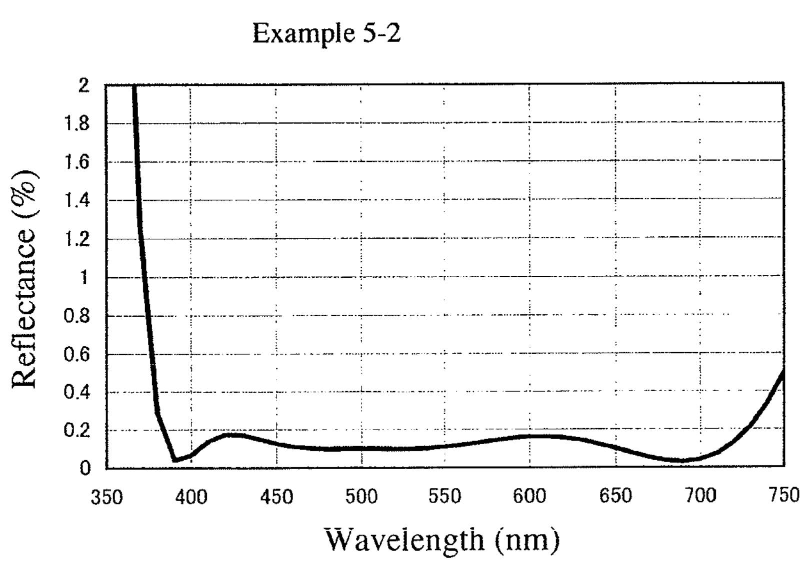

Example 5-2
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 59

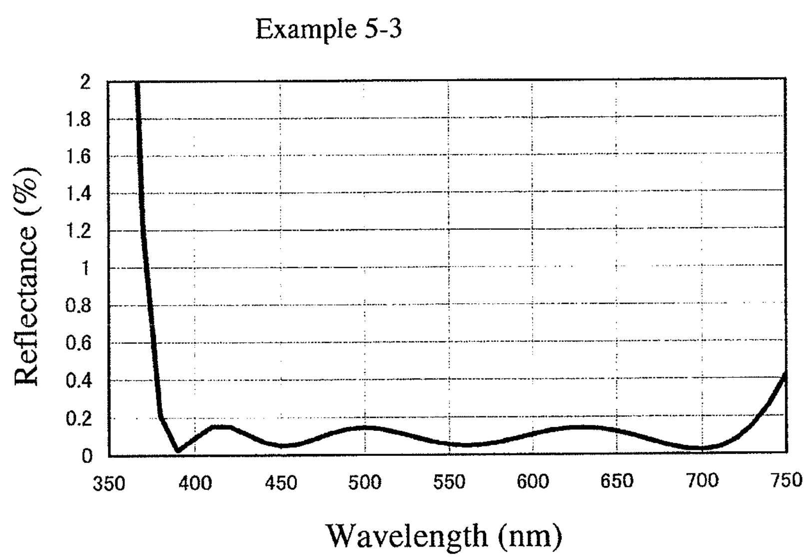

Example 5-3
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 60

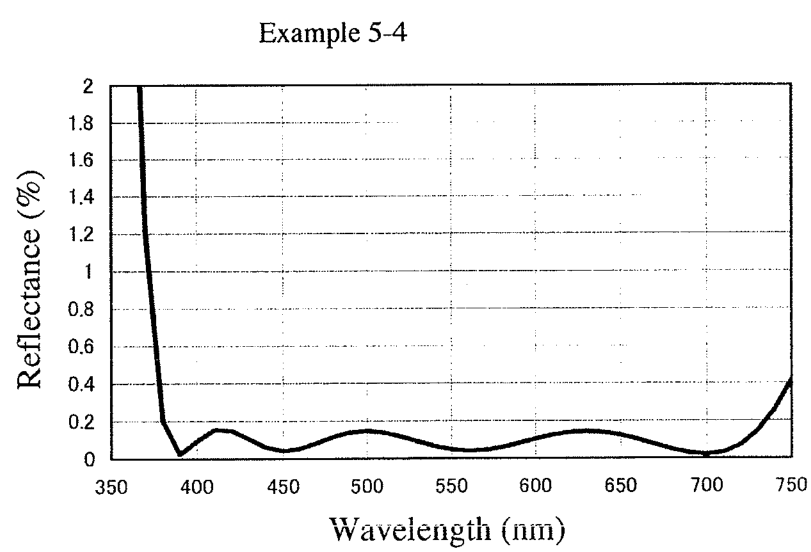

Example 5-4
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 61

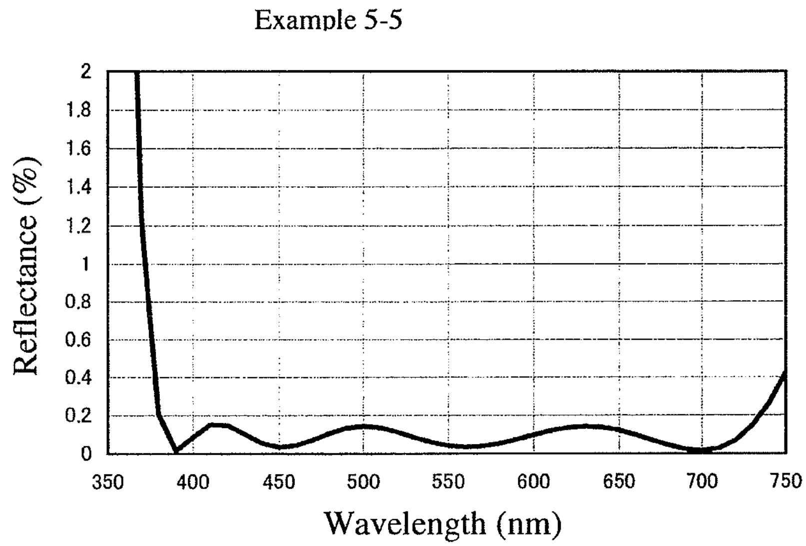

Example 5-5
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 62

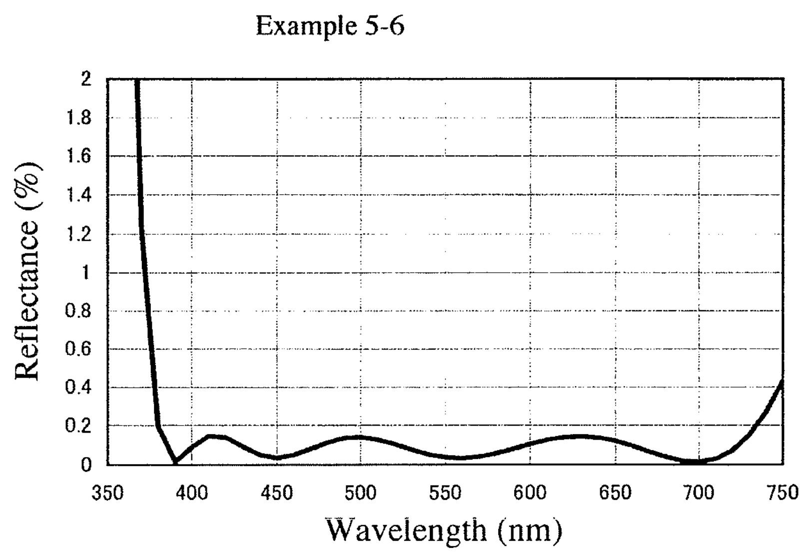

Example 5-6
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 63

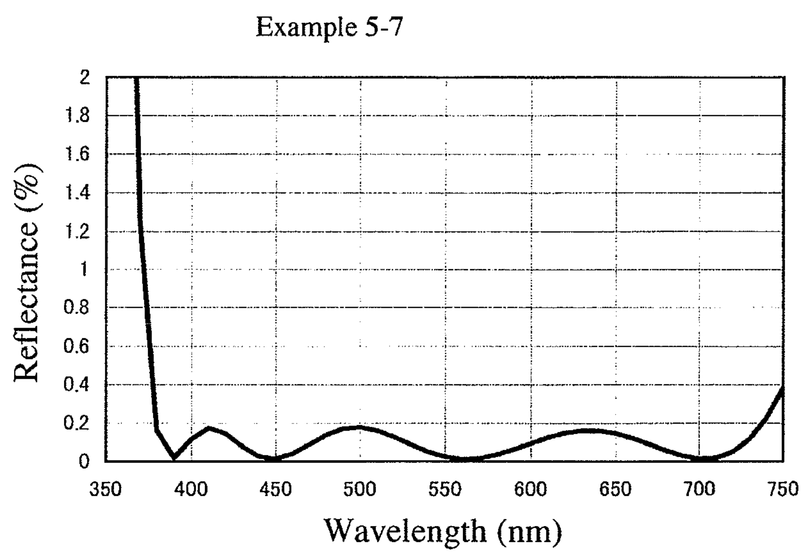

Example 5-7
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 64

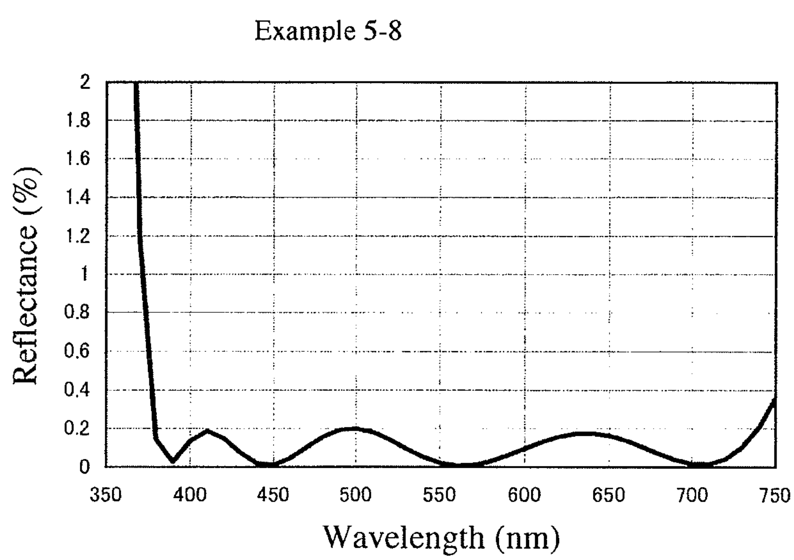

Example 5-8
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 65

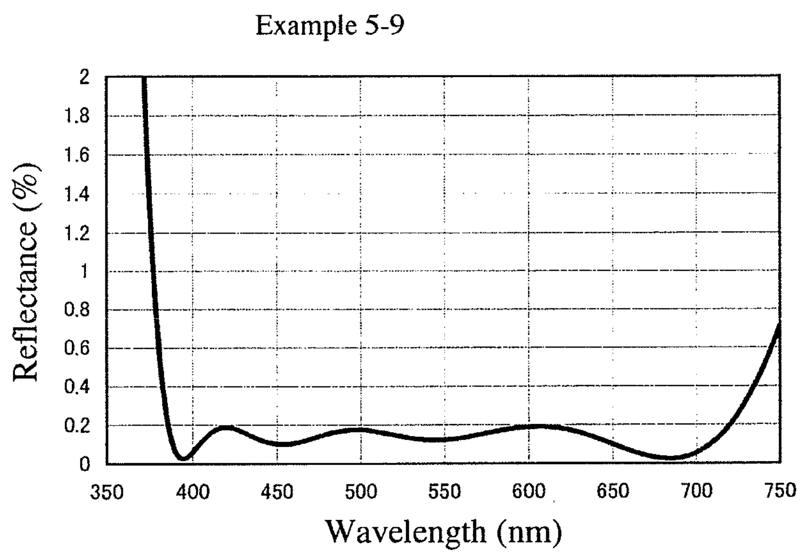

Example 5-9
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 66

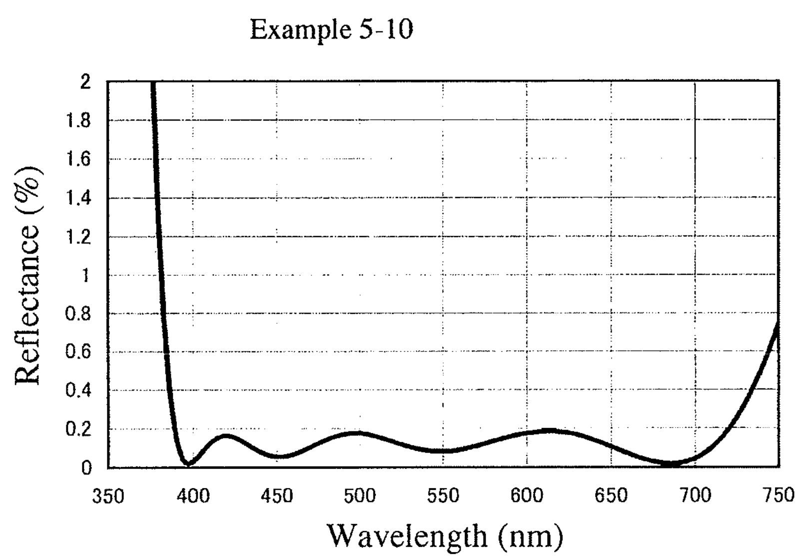

Example 5-10
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 67

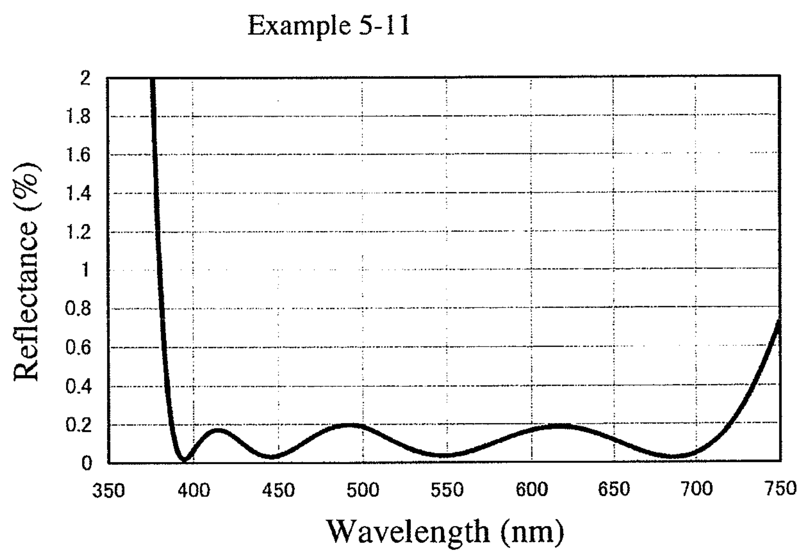

Example 5-11
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 68

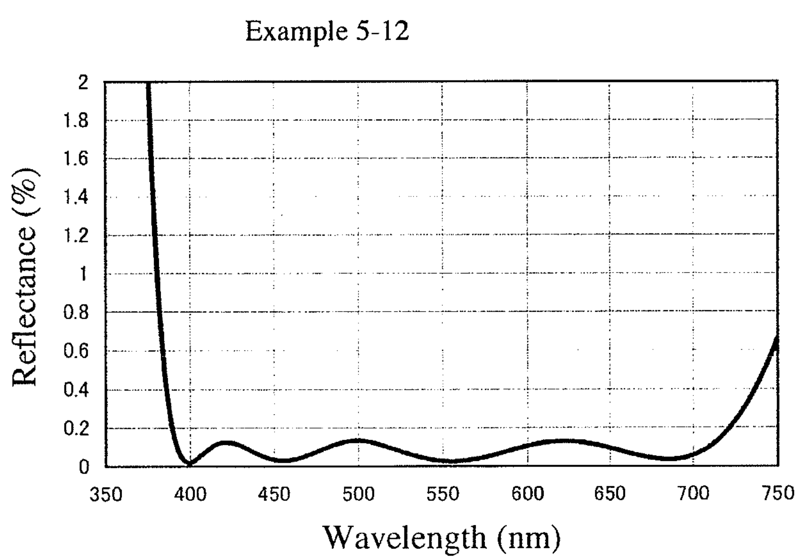

Example 5-12
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Reflectance (%)
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 69

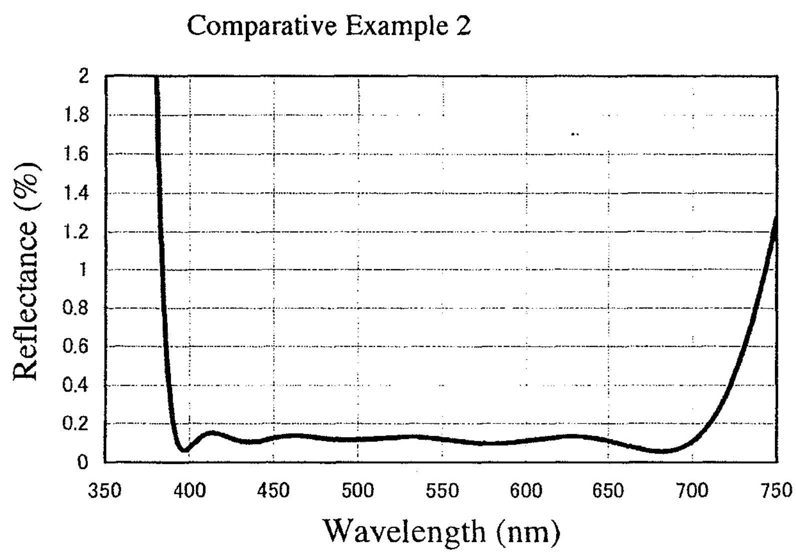

Comparative Example 2
Reflectance (%)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)

Fig. 70

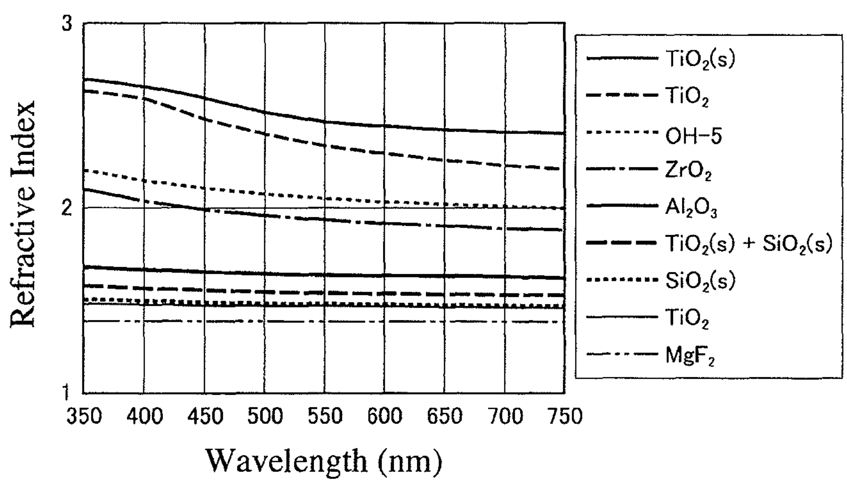

Refractive Index
3
2
1
350
400
450
500
550
600
650
700
750
Wavelength (nm)
TiO_2(s)
TiO_2
OH-5
ZrO_2
Al_2O_3
TiO_2(s) + SiO_2(s)
SiO_2(s)
TiO_2
MgF_2

Fig. 71

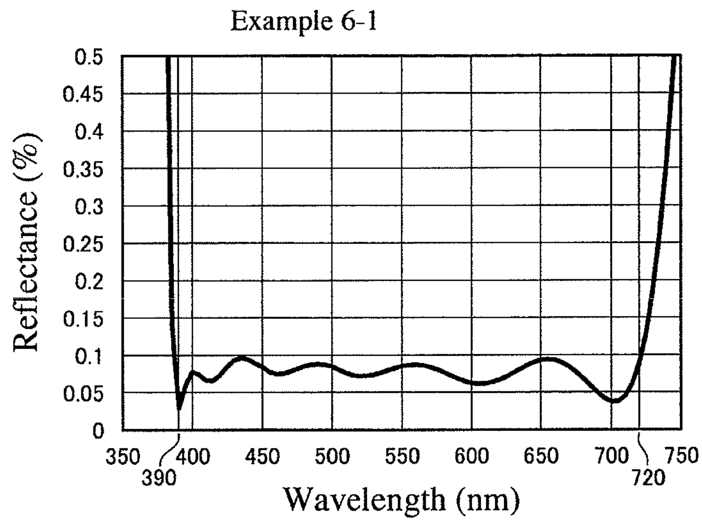

Example 6-1
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 72

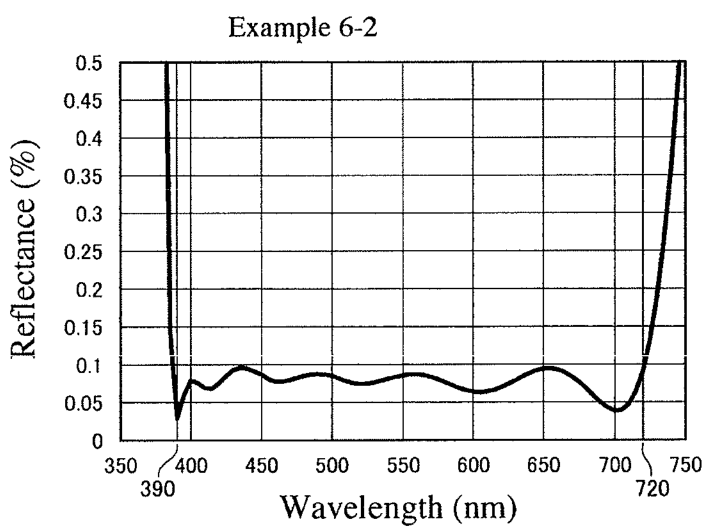
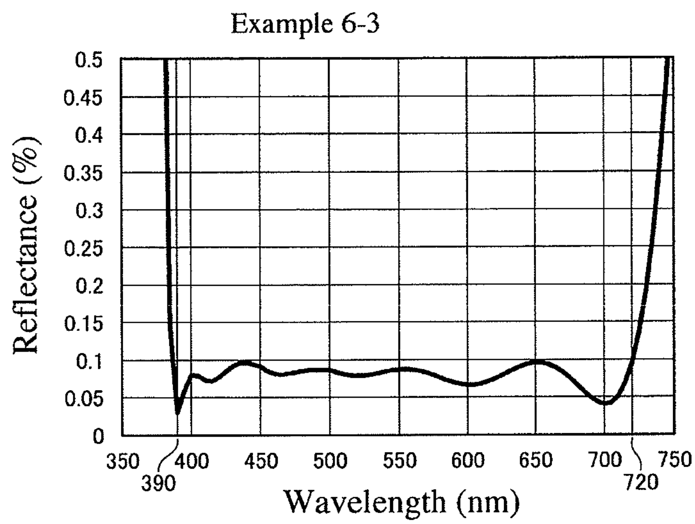
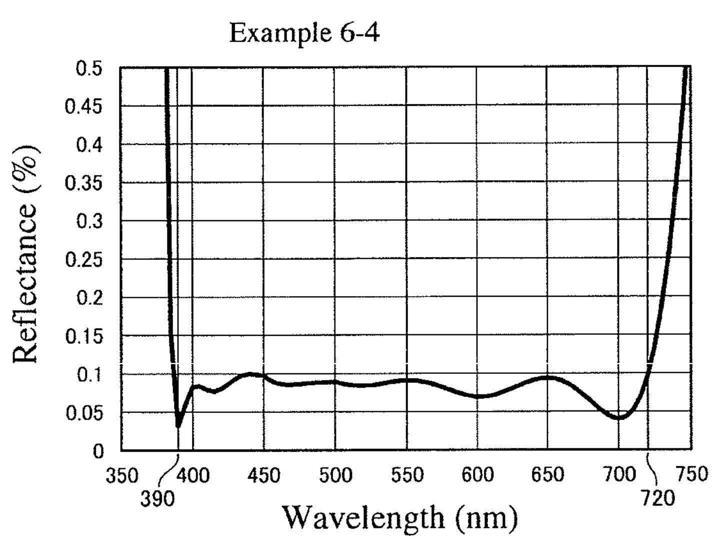

Example 6-2
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 73



Example 6-3
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
400
450
500
550
600
650
700
750
390
720
Wavelength (nm)

Fig. 74



Example 6-4
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
400
450
500
550
600
650
700
750
390
720
Wavelength (nm)

Fig. 75

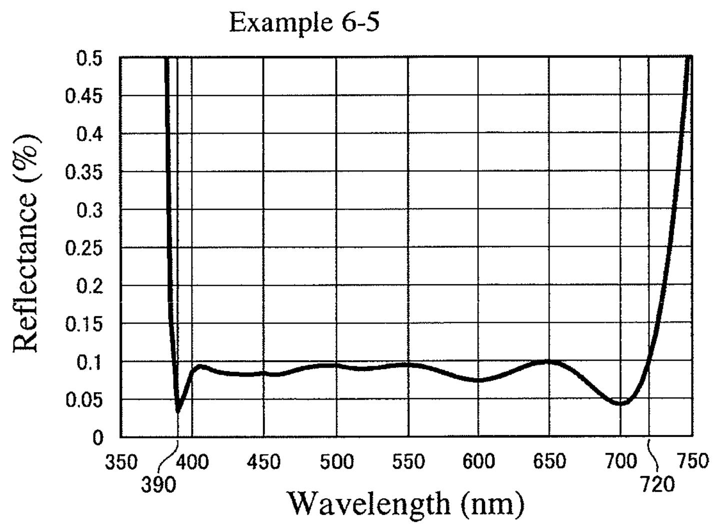

Example 6-5
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 76

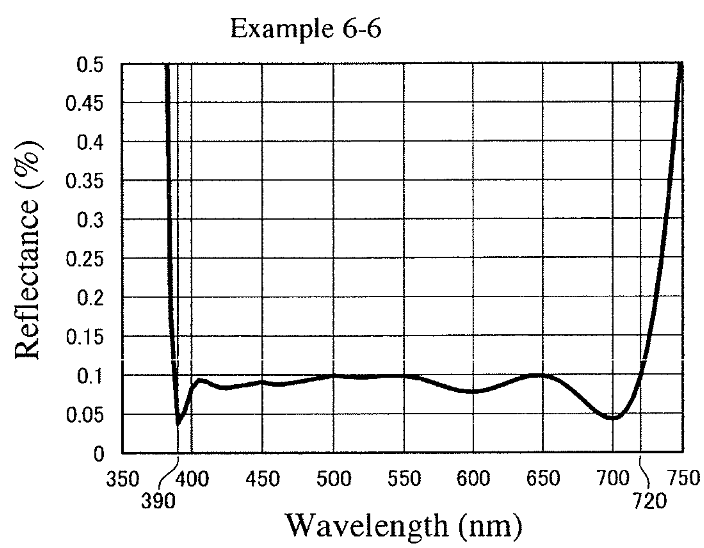

Example 6-6
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 77

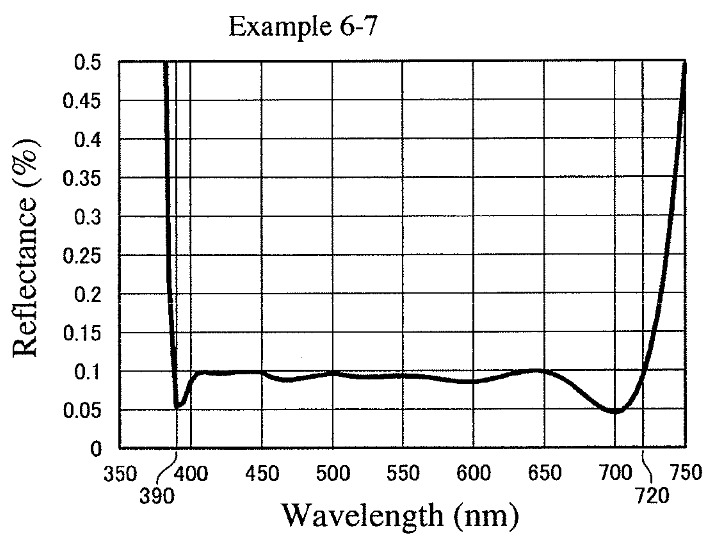

Example 6-7
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 78

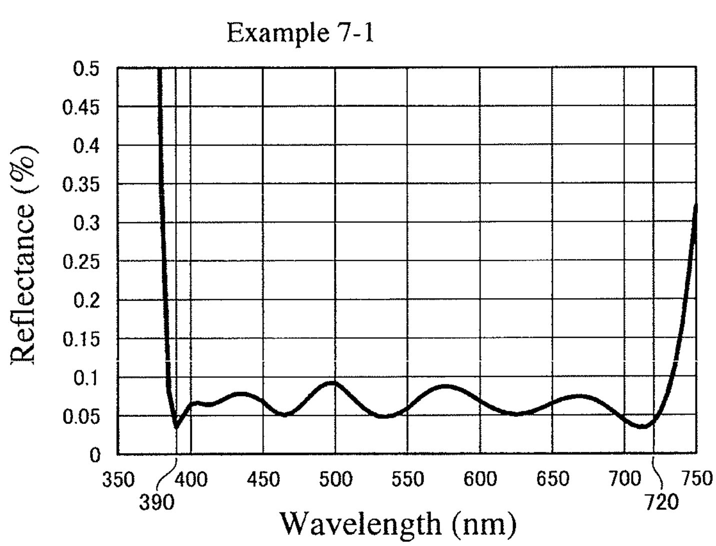

Example 7-1
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 79

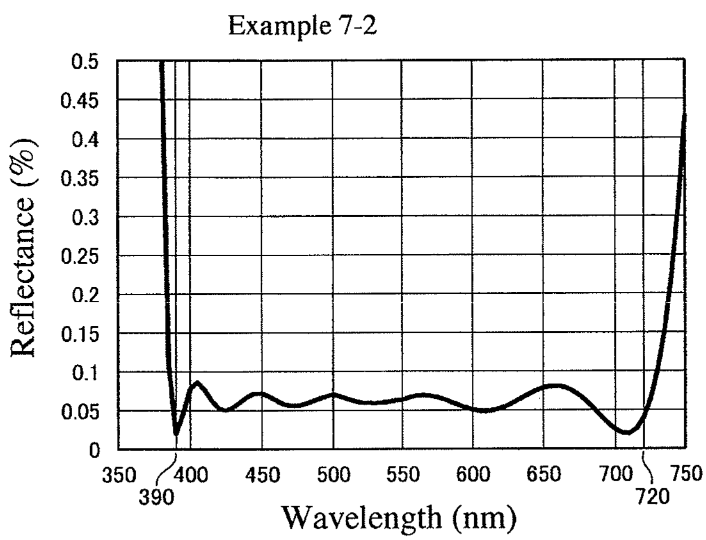

Example 7-2
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 80

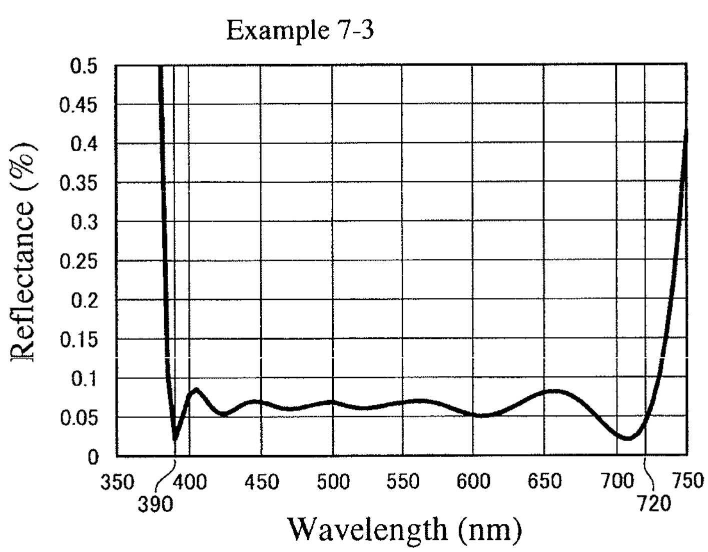

Example 7-3
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 81

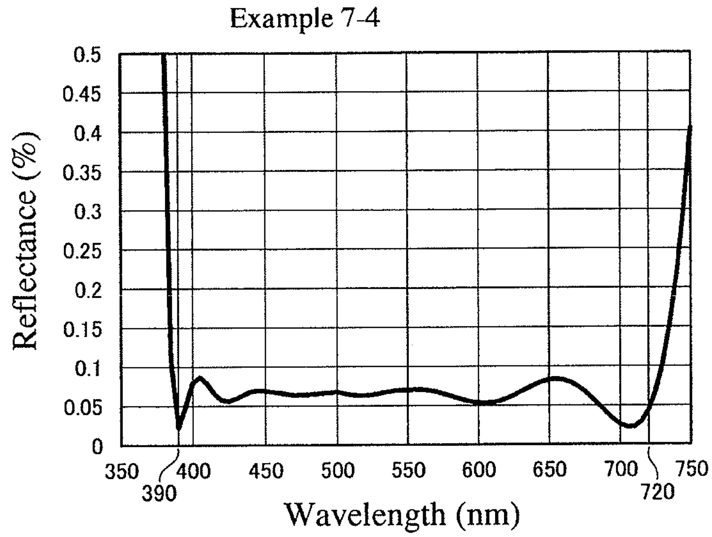

Example 7-4
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Reflectance (%)
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 82

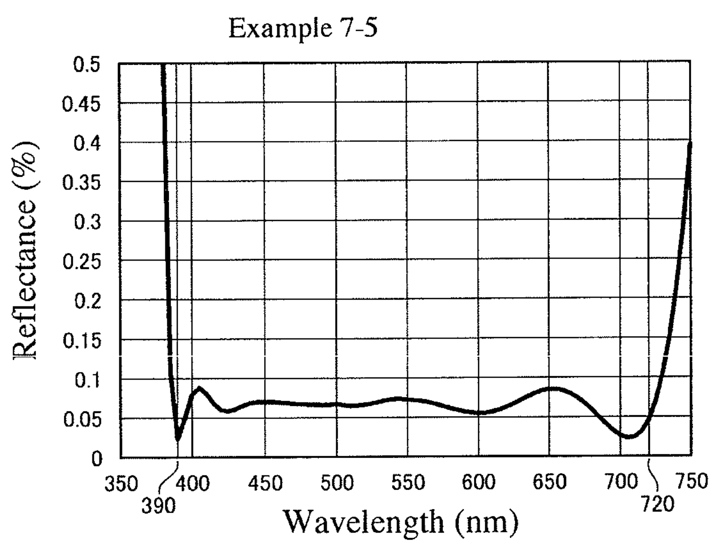

Example 7-5
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Reflectance (%)
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 83

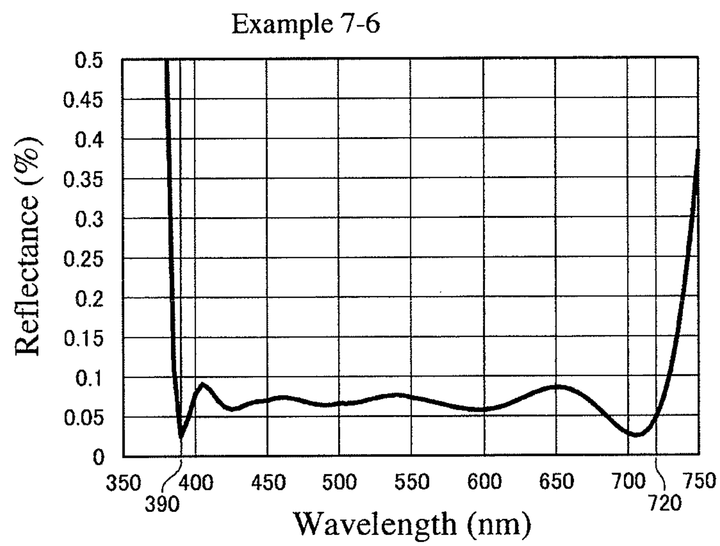

Example 7-6
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 84

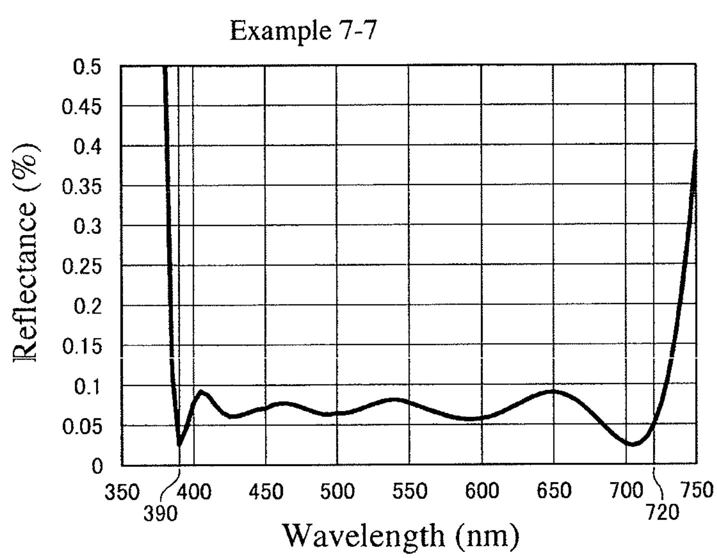

Example 7-7
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 85

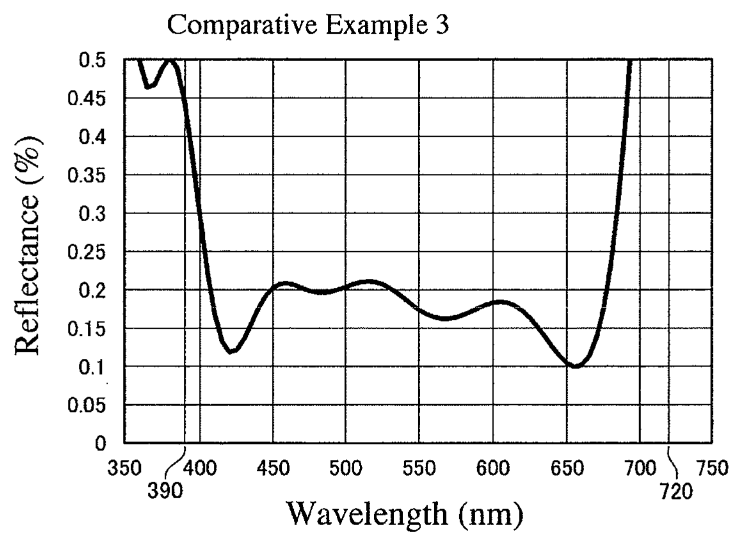

Comparative Example 3
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 86

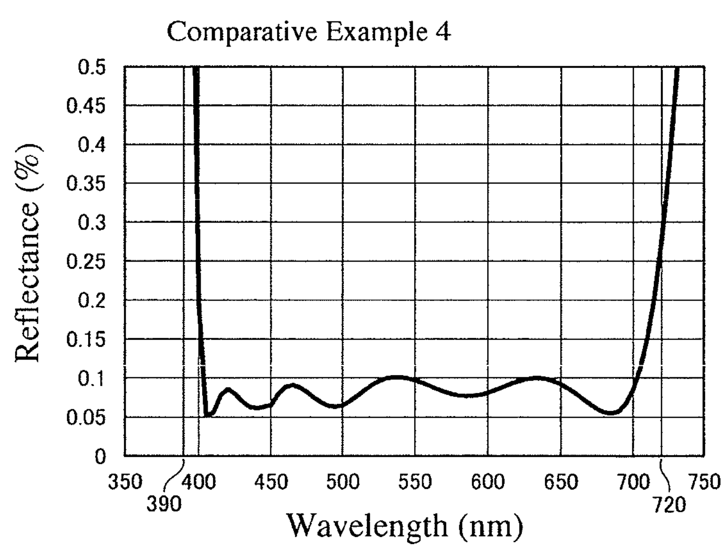
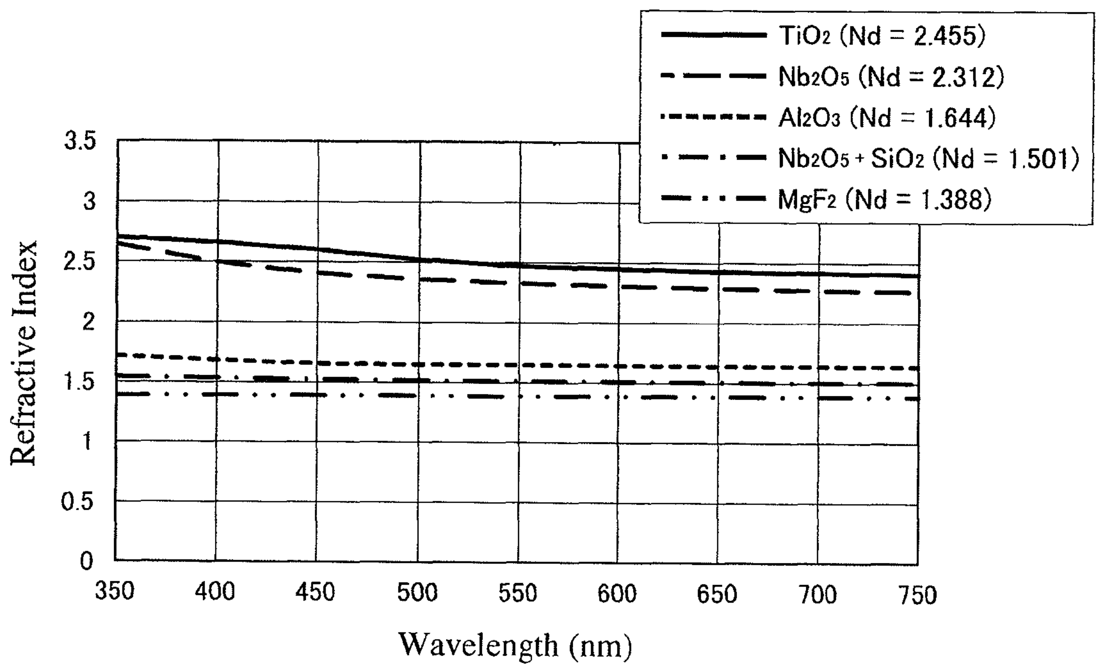

Comparative Example 4
Reflectance (%)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
350
390
400
450
500
550
600
650
700
720
750
Wavelength (nm)

Fig. 87



TiO2 (Nd = 2.455)
Nb2O5 (Nd = 2.312)
Al2O3 (Nd = 1.644)
Nb2O5 + SiO2 (Nd = 1.501)
MgF2 (Nd = 1.388)
3.5
3
2.5
2
1.5
1
0.5
0
Refractive Index
350
400
450
500
550
600
650
700
750
Wavelength (nm)

ANTI-REFLECTION COATING, OPTICAL MEMBER HAVING IT, AND OPTICAL EQUIPMENT COMPRISING SUCH OPTICAL MEMBER

FIELD OF THE INVENTION

The present invention relates to an anti-reflection coating having low reflectance in a wide wavelength range, an optical member such as a lens, a prism, a filter, etc. having such anti-reflection coating, and an optical equipment such as a TV camera, a video camera, a digital camera, an in-vehicle camera, a microscope, a telescope, etc., comprising such optical member.

BACKGROUND OF THE INVENTION

A single-focus lens and a zoom lens widely used for photographing and broadcasting are generally constituted by a large number of lenses, for example, about 10 to 40 lenses.

Increase in the number of lens leads to increase in the total amount of light reflected by lens surfaces, and entering of repeatedly reflected light into a photosensitive surface, causing problems such as flare and ghost, which extremely deteriorate the optical characteristics. Accordingly, these lenses have multi-layer anti-reflection coatings comprising dielectric layers having different refractive indices, each dielectric layers having optical thickness of ½λ or ¼λ to a center wavelength λ for utilizing interference effects.

For example, JP 2007-213021 A discloses an anti-reflection coating comprising first to eighth layers laminated in this order on a substrate, the first and fourth layers being made of a low-refractive-index material having a refractive index of 1.35-1.50 to a d-line having a wavelength of 587.56 nm, the third and fifth layers being made of an intermediate-refractive-index material having a refractive index of 1.55-1.85 to the d-line, and the second and sixth layers being made of a high-refractive-index material having a refractive index of 1.70-2.50, which is higher than that of the intermediate-refractive-index material, to the d-line. This anti-reflection coating has reflectance of about 0.15% or less in a wavelength range of about 400-700 nm.

JP 2002-267801 A discloses an anti-reflection coating comprising first to ninth thin, dielectric layers laminated in this order on a substrate, the second, fourth, sixth and eighth layers having a refractive index of N_h at a wavelength of 550 nm, the first, third, fifth and seventh layers having a refractive index of N_m at a wavelength of 550 nm, and the ninth layer having a refractive index of N_l at a wavelength 550 nm, meeting $2.00 \leq N_h \leq 2.20$, $1.50 \leq N_m \leq 1.80$, and $N_l \leq 1.46$. This anti-reflection coating has reflectance of about 0.2% or less in a wavelength range of about 400-680 nm.

JP 2002-107506 A discloses an anti-reflection coating having a design wavelength λ_0 of 550 nm and comprising 10 layers laminated on a substrate, the second, fourth, sixth and ninth layers having a refractive index of 2.00 or more at the design wavelength λ_0, the first and seventh layers having a refractive index of 1.50-1.80 at the design wavelength λ_0, and the third, fifth, eighth and tenth layers having a refractive index of 1.46 or less at the design wavelength λ_0. This anti-reflection coating has reflectance of about 0.2% or less in a wavelength range of about 400-710 nm.

JP 2001-100002 A discloses an anti-reflection coating comprising first to tenth thin, dielectric layers formed in this order on a substrate, the second, fourth, sixth and ninth layers having a refractive index of N_h at a wavelength of 550 nm, the first and eighth layers having a refractive index of N_m at a wavelength of 550 nm, the third, fifth, seventh and tenth layers having a refractive index of N_L at a wavelength of 550 nm, meeting $2.0 \leq N_h$, $1.5 \leq N_m \leq 1.8$, and $N_L \leq 1.46$. This anti-reflection coating has reflectance of about 0.2% or less in a wavelength range of about 410-690 nm.

However, these anti-reflection coatings have as narrow reflection-preventing ranges as about 300 nm in a wavelength range of 380-780 nm, which is generally called visible band. Human eyes have strong sensitivity particularly in a wavelength range of 390-720 nm in this visible band.

JP 2000-111702 A discloses a 14-layer anti-reflection coating comprising layers having a refractive index of 1.6 or more and layers having a refractive index of 1.5 or less for having wide-band reflection characteristics providing reflectance of 1% or less in a wavelength of 330-710 nm, and reflectance of 0.25% or less in a wavelength of 400-680 nm. However, this anti-reflection coating has reflectance of at most 0.25% or less in a reflection-preventing band, particularly in a visible band, failing to meet the recent demand of visible reflectance of 0.2% in digital camera lenses.

JP 2002-14203 A discloses an anti-reflection coating comprising 14-17 layers formed by TiO_2 having a refractive index of 2.407 and SiO_2 having a refractive index of 1.450 for having reflectance of 0.1% or less in a wavelength of 400-700 nm. However, the reflection-preventing wavelength range of this anti-reflection coating is as narrow as 300 nm in a wavelength range of 380-780 nm, which is generally called visible band.

Objects of the Invention

Accordingly, an object of the present invention is to provide an anti-reflection coating having excellent reflection-preventing characteristics in a wavelength range of 390-720 nm wider than the conventional reflection-preventing range of 300 nm.

Another object of the present invention is to provide an optical member having such an anti-reflection coating.

A further object of the present invention is to provide an optical equipment comprising such an optical member.

Disclosure of the Invention

As a result of intensive research in view of the above objects, the inventors have found that the alternate lamination of high-refractive-index layers and intermediate-refractive-index layers having large refractive index difference with a low-refractive-index layer as the uppermost layer provides an anti-reflection coating having low reflectance in a wide visible light band having a wavelength of 390-720 nm. The present invention has been completed based on such finding.

Thus, the anti-reflection coating according to the first embodiment of the present invention comprises first to ninth layers laminated in this order on a substrate for having reflectance of 0.2% or less to light in a visible wavelength range of 390-720 nm,

the second, fourth, sixth and eighth layers being high-refractive-index layers each formed by a high-refractive-index material having a refractive index of 2.21-2.70 to a helium d-line having a wavelength of 587.56 nm;

the first, third, fifth and seventh layers being intermediate-refractive-index layers each formed by an intermediate-refractive-index material having a refractive index of 1.40 or more and less than 1.55 to the d-line; and

the ninth layer being a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.35 or more and less than 1.40 to the d-line.

In the first embodiment, the refractive index difference between the intermediate-refractive-index layers and the high-refractive-index layers is preferably 0.67-1.30.

In the first embodiment, it is preferable that the high-refractive-index material is TiO_2, Nb_2O_5, or a mixture or compound of at least two of TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZnO, ZrO_2, In_2O_3, SnO_2 and HfO_2, that the intermediate-refractive-index material is SiO_2, YbF_3, YF_3, or a mixture or compound of at least two of SiO_2, Al_2O_3, CeF_3, NdF_3, GdF_3, LaF_3, YbF_3 and YF_3, and that the low-refractive-index material is MgF_2, AlF_3, or a mixture or compound of at least two of MgF_2, AlF_3 and SiO_2.

In the first embodiment, the substrate preferably has a refractive index of 1.40-2.10 to the d-line.

The anti-reflection coating according to the second embodiment of the present invention comprises first to seventh layers laminated in this order on an optical substrate with a refractive index of 1.43-1.73 to a helium d-line having a wavelength of 587.56 nm for having reflectance of 0.2% or less to light in a visible wavelength range of 390-720 nm,

the first layer having a refractive index of 1.37-1.56 to the d-line, and an optical thickness of 230-290 nm;

the second layer having a refractive index of 1.85-2.7 to the d-line, and an optical thickness of 20-80 nm;

the third layer having a refractive index of 1.37-1.52 to the d-line, and an optical thickness of 10-60 nm;

the fourth layer having a refractive index of 2.1-2.7 to the d-line, and an optical thickness of 130-220 nm;

the fifth layer having a refractive index of 1.37-1.52 to the d-line, and an optical thickness of 5-40 nm;

the sixth layer having a refractive index of 2.1-2.7 to the d-line, and an optical thickness of 20-90 nm; and

the seventh layer having a refractive index of 1.37-1.4 to the d-line, and an optical thickness of 100-160 nm.

In the second embodiment, the seventh layer preferably has a refractive index equal to or less than those of the first, third and fifth layers.

In the second embodiment, it is preferable that the first, third and fifth layers are made of MgF_2 or SiO_2, or a mixture or compound of SiO_2 with Al_2O_3, Nb_2O_5 or TiO_2, that the second, fourth and sixth layers are made of TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZrO_2, or any of their mixtures or compounds with SiO_2, and that the seventh layer is made of MgF_2, or a mixture or compound of MgF_2 with SiO_2, CaF_2 or LiF.

The anti-reflection coating according to the third embodiment of the present invention comprises first to fourteenth layers laminated in this order on an optical substrate having a refractive index of 1.43-2.01 to helium d-line having a wavelength of 587.56 nm,

the first, third, fifth, seventh, ninth, eleventh and thirteenth layers being high-refractive-index layers formed by high-refractive-index materials having refractive indices of 2.201-2.7 to the d-line;

the second, fourth, sixth, eighth, tenth and twelfth layers being intermediate-refractive-index layers formed by an intermediate-refractive-index material having a refractive index of 1.501-1.7 to the d-line;

the fourteenth layer being a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.37-1.44 to the d-line;

the first layer having an optical thickness of 5-45 nm;

the second layer having an optical thickness of 15-125 nm;

the third layer having an optical thickness of 40-130 nm;

the fourth layer having an optical thickness of 1-45 nm;

the fifth layer having an optical thickness of 135-175 nm;

the sixth layer having an optical thickness of 20-50 nm;

the seventh layer having an optical thickness of 30-65 nm;

the eighth layer having an optical thickness of 155-180 nm;

the ninth layer having an optical thickness of 10-35 nm;

the tenth layer having an optical thickness of 45-75 nm;

the eleventh layer having an optical thickness of 147-170 nm;

the twelfth layer having an optical thickness of 5-28 nm;

the thirteenth layer having an optical thickness of 55-85 nm; and

the fourteenth layer having an optical thickness of 120-145 nm.

In the third embodiment, the optical substrate is preferably made of optical glass, resins or optical crystals.

In the third embodiment, it is preferable that the high-refractive-index material is TiO_2 and/or Nb_2O_5, that the intermediate-refractive-index material is Al_2O_3, a mixture of SiO_2 with TiO_2, a mixture of SiO_2 with Nb_2O_5, a mixture of Al_2O_3 with TiO_2, or a mixture of Al_2O_3 with Nb_2O_5, and that the low-refractive-index material is MgF_2.

The optical member of the present invention comprises any one of the above-described anti-reflection coatings.

The optical equipment of the present invention comprises any one of the above-described optical members.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a view showing an anti-reflection coating according to the first embodiment of the present invention.

FIG. **2** is a view showing an anti-reflection coating according to the second embodiment of the present invention.

FIG. **3** is a view showing an anti-reflection coating according to the third embodiment of the present invention.

FIGS. **4-16** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 1-1 to 1-13.

FIGS. **17-29** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 2-1 to 2-13.

FIGS. **30-42** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 3-1 to 3-13.

FIGS. **43-55** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 4-1 to 4-13.

FIG. **56** is a graph showing the spectral characteristics of reflectance of the anti-reflection coating of Comparative Example 1.

FIGS. **57-68** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 5-1 to 5-12.

FIG. **69** is a graph showing the spectral characteristics of reflectance of the anti-reflection coating of Comparative Example 2.

FIG. **70** is a graph showing the refractive index dispersion of a coating material used for the anti-reflection coating of each Example 5-1 to 5-12.

FIGS. **71-77** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 6-1 to 6-8.

FIGS. **78-84** are graphs each showing the spectral characteristics of reflectance of the anti-reflection coating of each Example 8-1-7-8.

FIG. **85** is a graph showing the spectral characteristics of reflectance of the anti-reflection coating of Comparative Example 3.

FIG. **86** is a graph showing the spectral characteristics of reflectance of the anti-reflection coating of Comparative Example 4.

FIG. **87** is a graph showing the refractive index dispersion of a coating material used for the anti-reflection coating of each Example 6-1 to 6-8 and 7-1 to 7-8.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[1] First Embodiment

FIG. **1** is a view showing an anti-reflection coating **20** comprising first to ninth layers **21-29** laminated in this order on a substrate **10** according to the first embodiment of the present invention.

FIG. **1** shows a substrate **10** in a flat plate shape without intention of restriction, and any other substrates such as lenses, prisms, light guides, films and diffraction elements may be used. The substrate **10** preferably has a refractive index of 1.40-2.10 to a helium d-line having a wavelength of 587.56 nm, which may be called simply "d-line." Materials for the substrate **10** may be transparent materials such as glass, crystals, plastics, etc. Particularly preferable are optical glass such as FK03, FK5, BK7, SK20, SK14, LAK7, LAK10, LASF016, LASF04, SFL03, LASF08, NPH2, TAFD4, etc., Pyrex (trademark, nd=about 1.48), quartz (nd=about 1.46), blue plate glass (nd=about 1.51), white plate glass (nd=about 1.52), LUMICERA (trademark), Zerodur (trademark, nd=1.5424), fluorite (nd=1.434), sapphire, acrylics (nd=1.49), polycarbonates (nd=1.58), polyethylene terephthalate (nd=1.58), APEL (trademark, nd=1.54), ZEONEX (trademark, nd=1.53), ARTON (trademark, nd=1.52), etc.

In the anti-reflection coating **20**, the second, fourth, sixth and eighth layers **22**, **24**, **26**, **28** are high-refractive-index layers formed by high-refractive-index materials having refractive indices of 2.21-2.70 to the d-line, the first, third, fifth and seventh layers **21**, **23**, **25**, **27** are intermediate-refractive-index layers formed by an intermediate-refractive-index material having a refractive index of 1.40 or more and less than 1.55 to the d-line, and the ninth layer **29** is a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.35 or more and less than 1.40 to the d-line.

The anti-reflection coating **20** obtained by laminating the first to ninth layers **21-29** having the above refractive indices in this order on the substrate **10** has sufficiently reduced reflectance in a wider wavelength range with a small number of lamination. Specifically, it has as low reflectance as 0.2% or less to light having a wavelength range of 390-720 nm, which has particularly high sensitivity in a visible band of 380-780 nm.

With a large refractive index difference between the high-refractive-index layers of the second, fourth, sixth, and eighth layers **22**, **24**, **26**, **28** and the intermediate-refractive-index layers of the first, third, fifth and seventh layers **21**, **23**, **25**, **27**, the anti-reflection coating **20** has sufficiently reduced reflectance to light in a wide, visible wavelength range of 390-720 nm without suffering thickness increase. The refractive index difference between the high-refractive-index layer and the intermediate-refractive-index layer is preferably 0.67-1.30, more preferably 0.68-1.29.

The high-refractive-index materials may be TiO_2, Nb_2O_5, or mixtures or compounds of at least two of TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZnO, ZrO_2, In_2O_3, SnO_2 and HfO_2. TiO_2 and Nb_2O_5 can be used alone because they have high refractive indices. CeO_2, Ta_2O_5, ZnO, ZrO_2, In_2O_3, SnO_2 and HfO_2 can be used in combination, because they have refractive indices outside the range necessary for the high-refractive-index layer. Likewise, the intermediate-refractive-index materials may be SiO_2, YbF_3, YF_3, or mixtures or compounds of at least two of SiO_2, Al_2O_3, CeF_3, NdF_3, GdF_3, LaF_3, YbF_3 and YF_3. The low-refractive-index materials may be MgF_2, AlF_3, or mixtures or compounds of at least two of MgF_2, AlF_3 and SiO_2.

The high-refractive-index layer, the intermediate-refractive-index layer and the low-refractive-index layer are preferably formed by a physical deposition method such as a sputtering method, an ion plating method, a vapor deposition method, etc. It is particularly preferable to form the first to eighth layers by a sputtering method or an ion plating method, and to form the ninth layer by a high-precision vapor deposition method, thereby efficiently forming the anti-reflection coating **20** with a stable refractive index.

[2] Second Embodiment

FIG. **2** is a view showing an anti-reflection coating **40** according to the second embodiment of the present invention, which comprises first to seventh layers **41-47** laminated in this order on a substrate **30**.

The substrate **30** may be the same as in the first embodiment except that its refractive index to the d-line is 1.43-1.73. Particularly preferable are optical glass such as S-FPL53 (trademark, nd=1.43875), S-FSL5 (trademark, nd=1.48749), S-BSL7 (trademark, nd=1.51633), S-BAL50 (trademark, nd=1.55963), S-BSM14 (trademark, nd=1.60311), S-LAL7 (trademark, nd=1.65160), S-LAL10 (trademark, nd=1.72000), etc., Pyrex (trademark, nd-1.48), quartz (nd-1.46), blue plate glass (nd-1.51), white plate glass (nd-1.52), Zerodur (trademark, nd=1.5424), fluorite (nd=1.434), acrylics (nd=1.49), polycarbonates (nd=1.58), polyethylene terephthalate (nd=1.58), APEL (trademark, nd=1.54), ZEONEX (trademark, nd=1.53), ARTON (trademark, nd=1.52), etc.

In the anti-reflection coating **40**, the first layer **41** has a refractive index of 1.37-1.56 to the d-line and an optical thickness of 230-290 nm, the second layer **42** has a refractive index of 1.85-2.7 to the d-line and an optical thickness of 20-80 nm, the third layer **43** has a refractive index of 1.37-1.52 to the d-line and an optical thickness of 10-60 nm, the fourth layer **44** has a refractive index of 2.1-2.7 to the d-line and an optical thickness of 130-220 nm, the fifth layer **45** has a refractive index of 1.37-1.52 to the d-line and an optical thickness of 5-40 nm, the sixth layer **46** has a refractive index of 2.1-2.7 to the d-line and an optical thickness of 20-90 nm, and the seventh layer **47** has a refractive index of 1.37-1.4 to the d-line and an optical thickness of 100-160 nm.

The anti-reflection coating **40** has a 7-layer structure, which is obtained by substituting the first to third layers **21**, **22**, **23** in the anti-reflection coating **20** according to the first embodiment with the first layer **41**. With each layer having a refractive index and an optical thickness within the above ranges in the 7-layer structure, reflectance can be reduced sufficiently in a wide wavelength range with a small number UI lamination. Specifically, the reflectance to light in a wavelength range of 390-720 nm, which has high sensitivity among the visible band of 380-780 nm, is reduced to 0.2% or less.

With a large refractive index difference between the second, fourth and sixth layers **42**, **44**, **46** having a high refractive index and the first, third, fifth and seventh layers **41**, **43**, **45**, **47** having a low refractive index, the anti-reflection coating **40** has sufficiently reduced reflectance to light in a wide, visible wavelength range of 390-720 nm without suffering thickness increase. Particularly preferable is a large refractive index difference between the second, fourth and sixth layers **42**, **44**, **46** having a high refractive index and the first, third, fifth and seventh layers **41**, **43**, **45**, **47** having a low refractive index. Specifically, the refractive index difference between the second, fourth and sixth layers **42**, **44**, **46** and the first, third, fifth and seventh layers **41**, **43**, **45**, **47** is preferably 0.49-1.4, more preferably 0.7-1.33. The preferred refractive indices of the second, fourth and sixth layers **42**, **44**, **46** are 2.1-2.7.

The seventh layer **47** preferably has a refractive index equal to or less than those of the first, third and fifth layers **41**, **43**, **45**. With the seventh layer **47**, which is the outermost layer of the anti-reflection coating **40**, provided with a low refractive index, the anti-reflection coating **40** has reduced reflectance in a wide wavelength range. The refractive index of the seventh layer **47** is preferably 1.37 or more and less than 1.4, more preferably 1.375-1.395. Also, the first layer **41** preferably has a refractive index of 1.38-1.56, and the third and fifth layers **43**, **45** preferably have refractive indices of 1.38-1.52.

The refractive index of the seventh layer **47** is preferably lower than that of the first layer **41** by 0.0001-0.19, and lower than those of the third and fifth layers **43**, **45** by 0.001-0.19. With the refractive index of the seventh layer **47**, which is the outermost layer of the anti-reflection coating **40**, lower than those of the first, third and fifth layers **41**, **43**, **45**, the anti-reflection coating **40** has further reduced reflectance.

Materials for the second, fourth and sixth layers **42**, **44**, **46** may be TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZrO_2, or their mixtures or compounds with SiO_2. TiO_2, Nb_2O_5, CeO_2, Ta_2O_5 and ZrO_2 can be used alone for the second, fourth and sixth layers **42**, **44**, **46**, because they have high refractive indices. They are also usable in combination with SiO_2. Materials for the first, third and fifth layers **41**, **43**, **45** may be MgF_2, SiO_2, or mixtures or compounds of SiO_2 with Al_2O_3, Nb_2O_5 or TiO_2. Materials for the seventh layer **47** may be MgF_2, or mixtures or compounds of MgF_2 with SiO_2, CaF_2 or LiF.

The first to seventh layers **41**-**47** are preferably formed by the above physical deposition method. It is particularly preferable to form the first to sixth layers by a sputtering method or an ion plating method, and to form the seventh layer by a high-precision vapor deposition method, thereby efficiently forming the anti-reflection coating **40** with a stable refractive index.

[3] Third Embodiment

FIG. **3** is a view showing an anti-reflection coating **60** comprising first to fourteenth layers **61**-**74** laminated in this order on a substrate **50** according to the third embodiment of the present invention.

The substrate **50** may be the same as in the first embodiment except that its refractive index to the d-line is 1.43-2.01. Particularly preferable are optical glass such as FK03, FK5, BK7, SK20, SK14, LAK7, LAK10, LASF016, LASF04, SFL03, LASF08, NPH2, TAFD4, S-FPL53 (trademark, nd=1.4388), S-PSL5 (trademark, nd=1.48749), S-BSL7 (trademark, nd=1.5163), S-BAL50 (trademark, nd=1.55963), S-BSM14 (trademark, nd=1.60311), S-LAL7 (trademark, nd=1.65160), S-LAL10 (trademark, nd=1.72000), etc., Pyrex (trademark, nd=about 1.48), quartz (nd=about 1.46), blue plate glass (nd=about 1.51), white plate glass (nd=about 1.52), LUMICERA (trademark), Zerodur (trademark, nd=1.5424), fluorite (nd=1.434), sapphire, acrylics (nd=1.49), polycarbonates (nd=1.58), polyethylene terephthalate (nd=1.58), APEL (trademark, nd=1.54), ZEONEX (trademark, nd=1.53), ARTON (trademark, nd=1.52), etc.

In the anti-reflection coating **60**, the first, third, fifth, seventh, ninth, eleventh and thirteenth layers **61**, **63**, **65**, **67**, **69**, **71**, **73** are high-refractive-index layers formed by high-refractive-index materials having refractive indices of 2.201-2.7 to the d-line, the second, fourth, sixth, eighth, tenth and twelfth layers **62**, **64**, **66**, **68**, **70**, **72** are intermediate-refractive-index layers formed by intermediate-refractive-index materials having refractive indices of 1.501-1.7 to the d-line, and the fourteenth layer **74** is a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.37-1.44 to the d-line.

The anti-reflection coating **60** having the above layer structure, which is formed on the substrate **50**, has sufficiently reduced reflectance in a wide wavelength range including a visible long-wavelength range. Specifically, the reflectance to incident light perpendicular to the substrate **50** can be reduced to 0.1% or less in a wavelength bandwidth of 330 nm between 390 nm and 720 nm.

The high-refractive-index layers preferably have refractive indices of 2.201-2.500, the intermediate-refractive-index layers preferably have refractive indices of 1.501-1.690, and the low-refractive-index layer preferably has a refractive index of 1.370-1.430, thereby reducing reflectance in a wavelength bandwidth of 330 nm between 390 nm and 720 nm.

The high-refractive-index materials may be TiO_2 and/or Nb_2O_5. The intermediate-refractive-index materials may be Al_2O_3, mixtures of SiO_2 with TiO_2 or Nb_2O_5, or mixtures of Al_2O_3 with TiO_2 or Nb_2O_5. The low-refractive-index material may be MgF_2.

The first layer **61** has an optical thickness of 5-45 nm, the second layer **62** has an optical thickness of 15-125 nm, the third layer **63** has an optical thickness of 40-130 nm, the fourth layer **64** has an optical thickness of 1-45 nm, the fifth layer **65** has an optical thickness of 135-175 nm, the sixth layer **66** has an optical thickness of 20-50 nm, the seventh layer **67** has an optical thickness of 30-65 nm, the eighth layer **68** has an optical thickness of 155-180 nm, the ninth layer **69** has an optical thickness of 10-35 nm, the tenth layer **70** has an optical thickness of 45-75 nm, the eleventh layer **71** has an optical thickness of 147-170 nm, the twelfth layer **72** has an optical thickness of 5-28 nm, the thirteenth layer **73** has an optical thickness of 55-85 nm, and the fourteenth layer **74** has an optical thickness of 120-145 nm.

The first to fourteenth layers **61**-**74** are preferably formed by the above physical deposition method. It is particularly preferable to form the first to thirteenth layers by a sputtering method or an ion plating method, and to form the fourteenth layer by a high-precision vapor deposition method, thereby efficiently forming the anti-reflection coating **60** with a stable refractive index.

[4] Optical Members and Optical Equipments

The optical members of the present invention comprising the above anti-reflection coatings have excellent refractive index characteristics, suitable as lenses, prisms, filters, etc. for optical equipments such as TV cameras, video cameras, digital cameras, in-vehicle cameras, microscopes, telescopes, etc.

Though the embodiments of the present invention have been explained referring to the attached drawings, proper modifications and additions may be made within the scope of the present invention. For example, the anti-reflection coating

20, 40, 60 may comprise additional films unless its characteristics are affected. Also, thin films having different refractive indices may be interposed between any adjacent layers, and at least one layer may be, substituted by pluralities of films, unless the characteristics of the anti-reflection coating are affected.

It should be noted that the layer materials are not restricted to those described above, but any materials having desired refractive indices may be used.

refractive index of the substrate **10** and the optical thickness of each layer in the anti-reflection coating **20** in each Example 1-1 to 1-13 are shown in Table 1. Using a design wavelength λ_0 of 550 nm, the optical thickness of each layer is expressed by number×λ_0 in Table 1. The spectral reflectance of each anti-reflection coating **20** of Examples 1-1 to 1-13 to perpendicular incident light was calculated by simulation, with reflection on an opposite surface of the substrate **10** to the anti-reflection coating **20** neglected. The calculation results are shown in FIG. **4-16**.

TABLE 1

	Substrate		Optical Thickness (×λ_0) of Each Layer			
Examples	Material	Refractive Index	1st Layer SiO_2	2nd Layer TiO_2	3rd Layer SiO_2	4th Layer TiO_2
1-1	FK03	1.44	0.11	0.02	0.13	0.1
1-2	FK5	1.49	0.11	0.03	0.13	0.1
1-3	BK7	1.52	0.11	0.03	0.14	0.1
1-4	SK20	1.56	0.11	0.04	0.14	0.11
1-5	SK14	1.60	0.11	0.04	0.14	0.11
1-6	LAK7	1.65	0.1	0.05	0.14	0.11
1-7	LAK10	1.72	0.09	0.05	0.14	0.11
1-8	LASF016	1.77	0.08	0.06	0.13	0.12
1-9	LASF04	1.82	0.07	0.07	0.12	0.12
1-10	SFL03	1.85	0.07	0.07	0.12	0.12
1-11	LASF08	1.88	0.06	0.08	0.11	0.13
1-12	NPH2	1.92	0.06	0.09	0.1	0.13
1-13	TAFD40	2.00	0.06	0.09	0.1	0.14

	Optical Thickness (×λ_0) of Each Layer				
Examples	5th Layer SiO_2	6th Layer TiO_2	7th Layer SiO_2	8th Layer TiO_2	9th Layer MgF_2
1-1	0.05	0.31	0.04	0.1	0.24
1-2	0.05	0.31	0.04	0.1	0.25
1-3	0.05	0.32	0.04	0.1	0.25
1-4	0.05	0.32	0.04	0.1	0.25
1-5	0.06	0.32	0.04	0.1	0.25
1-6	0.05	0.32	0.04	0.1	0.25
1-7	0.06	0.32	0.04	0.1	0.25
1-8	0.05	0.33	0.04	0.1	0.25
1-9	0.05	0.33	0.04	0.1	0.25
1-10	0.05	0.33	0.04	0.1	0.25
1-11	0.05	0.33	0.04	0.1	0.25
1-12	0.05	0.33	0.04	0.1	0.25
1-13	0.05	0.33	0.04	0.1	0.25

The optimum optical thickness [refractive index (n)× physical thickness (d)] of each layer can be determined by computer simulation using the refractive indices of the substrate and all layers.

The present invention will be explained in further detail by Examples below without intention of restricting the present invention thereto.

EXAMPLES 1-1 TO 1-13

In each anti-reflection coating **20** according to the first embodiment, which comprised high-refractive-index layers **22**, **24**, **26** and **28** made of TiO_2 having a refractive index of 2.46 to the d-line, intermediate-refractive-index layers **21**, **23**, **25** and **27** made of SiO_2 having a refractive index of 1.48 to the d-line, and a low-refractive-index layer **29** made of MgF_2 having a refractive index of 1.39 to the d-line, with air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **21-29** for each substrate **10** was determined by simulation. The material and

EXAMPLES 2-1 TO 2-13

In each anti-reflection coating **20** according to the first embodiment, which comprised high-refractive-index layers **22**, **24**, **26** and **28** made of Nb_2O_5 having a refractive index of 2.31 to the d-line, intermediate-refractive-index layers **21**, **23**, **25** and **27** made of SiO_2 having a refractive index of 1.48 to the d-line, and a low-refractive-index layer **29** made of MgF_2 having a refractive index of 1.39 to the d-line, with air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **21-29** for each substrate **10** was calculated by simulation. The material and refractive index of the substrate **10** and the optical thickness of each layer in the anti-reflection coating **20** in each Example 2-1 to 2-13 are shown in Table 2. The spectral reflectance of each anti-reflection coating **20** of Examples 2-1 to 2-13 to perpendicular incident light was calculated by simulation. The calculation results are shown in FIGS. **17-29**.

TABLE 2

	Substrate		Optical Thickness ($\times\lambda_0$) of Each Layer			
Examples	Material	Refractive Index	1st Layer SiO_2	2nd Layer Nb_2O_5	3rd Layer SiO_2	4th Layer Nb_2O_5
2-1	FK03	1.44	0.07	0.02	0.15	0.09
2-2	FK5	1.49	0.14	0.03	0.14	0.1
2-3	BK7	1.52	0.21	0.02	0.16	0.09
2-4	SK20	1.56	0.16	0.03	0.17	0.09
2-5	SK14	1.60	0.15	0.03	0.18	0.09
2-6	LAK7	1.65	0.12	0.04	0.17	0.09
2-7	LAK10	1.72	0.09	0.06	0.15	0.11
2-8	LASF016	1.77	0.08	0.06	0.13	0.11
2-9	LASF04	1.82	0.07	0.07	0.12	0.12
2-10	SFL03	1.85	0.07	0.08	0.12	0.12
2-11	LASF08	1.88	0.06	0.08	0.11	0.12
2-12	NPH2	1.92	0.06	0.09	0.11	0.13
2-13	TAFD40	2.00	0.05	0.1	0.1	0.13

	Optical Thickness ($\times\lambda_0$) of Each Layer				
Examples	5th Layer SiO_2	6th Layer Nb_2O_5	7th Layer SiO_2	8th Layer Nb_2O_5	9th Layer MgF_2
2-1	0.06	0.3	0.04	0.11	0.24
2-2	0.06	0.3	0.04	0.11	0.24
2-3	0.06	0.31	0.04	0.11	0.24
2-4	0.07	0.31	0.04	0.11	0.24
2-5	0.07	0.31	0.04	0.11	0.24
2-6	0.07	0.32	0.04	0.11	0.24
2-7	0.06	0.32	0.04	0.11	0.24
2-8	0.06	0.33	0.04	0.11	0.24
2-9	0.06	0.33	0.04	0.11	0.24
2-10	0.06	0.33	0.04	0.11	0.25
2-11	0.06	0.33	0.04	0.11	0.24
2-12	0.06	0.33	0.04	0.11	0.24
2-13	0.05	0.34	0.04	0.11	0.24

EXAMPLES 3-1 TO 3-13

In each anti-reflection coating **20** according to the first embodiment, which comprised high-refractive-index layers **22**, **24**, **26** and **28** made of a mixture of Nb_2O_5 and HfO_2 having a refractive index of 2.21 to the d-line, intermediate-refractive-index layers **21**, **23**, **25** and **27** made of SiO_2 having a refractive index of 1.47 to the d-line, and a low-refractive-index layer **29** made of MgF_2 having a refractive index of 1.39 to the d-line, with air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **21-29** for each substrate **10** was calculated by simulation. The material and refractive index of the substrate **10** and the optical thickness of each layer in the anti-reflection coating **20** in Examples 3-1 to 3-13 are shown in Table 3. The spectral reflectance of each anti-reflection coating **20** of Examples 3-1 to 3-13 to perpendicular incident light was calculated by simulation. The calculation results are shown in FIGS. **30-42**.

TABLE 3

			Optical Thickness ($\times\lambda_0$) of Each Layer			
	Substrate			2nd Layer		4th Layer
Examples	Material	Refractive Index	1st Layer SiO_2	Nb_2O_5 + HfO_2	3rd Layer SiO_2	Nb_2O_5 + HfO_2
3-1	FK03	1.44	0.31	0.01	0.59	0.07
3-2	FK5	1.49	0.55	0.01	0.6	0.07
3-3	BK7	1.52	0.05	0.01	0.56	0.07
3-4	SK20	1.56	0.05	0.01	0.46	0.07
3-5	SK14	1.60	0.06	0.01	0.44	0.07
3-6	LAK7	1.65	0.07	0.02	0.43	0.06
3-7	LAK10	1.72	0.07	0.02	0.43	0.06
3-8	LASF016	1.77	0.07	0.03	0.43	0.06
3-9	LASF04	1.82	0.07	0.04	0.43	0.06
3-10	SFL03	1.85	0.07	0.04	0.43	0.06
3-11	LASF08	1.88	0.07	0.05	0.44	0.06
3-12	NPH2	1.92	0.07	0.05	0.44	0.05
3-13	TAFD40	2.00	0.06	0.06	0.44	0.05

TABLE 3-continued

Examples	Optical Thickness (×λ_0) of Each Layer: 5th Layer SiO_2	6th Layer Nb_2O_5 + HfO_2	7th Layer SiO_2	8th Layer Nb_2O_5 + HfO_2	9th Layer MgF_2
3-1	0.08	0.3	0.03	0.12	0.24
3-2	0.08	0.3	0.03	0.12	0.24
3-3	0.08	0.3	0.03	0.12	0.24
3-4	0.08	0.29	0.03	0.12	0.24
3-5	0.08	0.28	0.03	0.13	0.24
3-6	0.08	0.28	0.03	0.13	0.24
3-7	0.07	0.27	0.03	0.12	0.24
3-8	0.07	0.27	0.03	0.12	0.24
3-9	0.07	0.27	0.03	0.12	0.23
3-10	0.07	0.27	0.03	0.12	0.23
3-11	0.06	0.27	0.03	0.12	0.23
3-12	0.07	0.27	0.03	0.12	0.23
3-13	0.06	0.27	0.02	0.12	0.23

EXAMPLES 4-1 TO 4-13

In each anti-reflection coating **20** according to the first embodiment, which comprised high-refractive-index layers **22**, **24**, **26** and **28** made of TiO_2 having a refractive index of 2.30 to the d-line, intermediate-refractive-index layers **21**, **23**, **25** and **27** made of a mixture of Al_2O_3 and SiO_2 having a refractive index of 1.54 to the d-line, and a low-refractive-index layer **29** made of MgF_2 having a refractive index of 1.39 to the d-line, with air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **21-29** for each substrate **10** was calculated by simulation. The material and refractive index of the substrate **10** and the optical thickness of each layer in the anti-reflection coatings **20** in each Example 4-1 to 4-13 are shown in Table 4. The spectral reflectance of each anti-reflection coating **20** of Examples 4-1 to 4-13 to perpendicular incident light was calculated by simulation. The calculation results are shown in FIGS. **43-55**.

TABLE 4

Examples	Substrate: Material	Substrate: Refractive Index	Optical Thickness (×λ_0) of Each Layer: 1st Layer Al_2O_3 + SiO_2	2nd Layer TiO_2	3rd Layer Al_2O_3 + SiO_2	4th Layer TiO_2
4-1	FK03	1.44	0.31	0.02	0.57	0.07
4-2	FK5	1.49	0.31	0.02	0.57	0.07
4-3	BK7	1.52	0.3	0.01	0.57	0.07
4-4	SK20	1.56	0.55	0.01	0.57	0.06
4-5	SK14	1.60	0.02	0.01	0.54	0.07
4-6	LAK7	1.65	0.01	0.01	0.52	0.07
4-7	LAK10	1.72	0.06	0.01	0.43	0.07
4-8	LASF016	1.77	0.07	0.01	0.43	0.07
4-9	LASF04	1.82	0.07	0.02	0.43	0.07
4-10	SFL03	1.85	0.07	0.02	0.43	0.07
4-11	LASF08	1.88	0.07	0.03	0.42	0.07
4-12	NPH2	1.92	0.07	0.03	0.44	0.07
4-13	TAFD40	2.00	0.07	0.04	0.44	0.06

Examples	Optical Thickness (×λ_0) of Each Layer: 5th Layer Al_2O_3 + SiO_2	6th Layer TiO_2	7th Layer Al_2O_3 + SiO_2	8th Layer TiO_2	9th Layer MgF_2
4-1	0.07	0.3	0.04	0.1	0.24
4-2	0.07	0.33	0.04	0.09	0.24
4-3	0.07	0.36	0.04	0.08	0.23
4-4	0.07	0.37	0.04	0.08	0.23
4-5	0.07	0.35	0.04	0.09	0.23
4-6	0.07	0.32	0.04	0.09	0.23
4-7	0.07	0.27	0.04	0.1	0.24
4-8	0.07	0.27	0.04	0.11	0.24
4-9	0.07	0.27	0.04	0.1	0.24
4-10	0.07	0.27	0.04	0.1	0.24
4-11	0.06	0.27	0.04	0.1	0.23
4-12	0.06	0.27	0.04	0.1	0.24
4-13	0.06	0.27	0.04	0.1	0.23

As is clear from FIGS. **4-55**, the resultant anti-reflection coatings had the maximum reflectance of 0.2% or less in a wavelength bandwidth of 330 nm between 390 nm and 720 nm. This indicates that the anti-reflection coating according to the first embodiment of the present invention has sufficiently reduced reflectance in a wide wavelength range with a small number of lamination, thereby suppressing problems such as flare and ghost, which extremely deteriorate the optical characteristics, to obtain excellent color balance.

COMPARATIVE EXAMPLE 1

In an anti-reflection coating **20** formed on a substrate **10** made of BSL7 having a refractive index of 1.52, which comprised high-refractive-index layers **22**, **24**, **26** and **28** made of ZrO_2+TiO_2 having a refractive index of 2.11 to light in a wavelength of 550 nm, intermediate-refractive-index layers **21**, **23**, **25** and **27** made of Al_2O_3 having a refractive index of 1.62 to light in a wavelength of 550 nm, and a low-refractive-index layer **29** made of MgF_2 having a refractive index of 1.38 to light in a wavelength of 550 nm, with air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **21-29** for the substrate **10** was calculated by simulation. The optical thickness of each layer in the anti-reflection coating **20** is shown in Table 5. The spectral reflectance of the anti-reflection coating **20** to perpendicular incident light was calculated by simulation. The calculation results are shown in FIG. **56**.

TABLE 5

Layer	Material	Optical Thickness ($\times\lambda_0$)
Substrate	BSL7	—
1st Layer	Al_2O_3	0.167
2nd Layer	$ZrO_2 + TiO_2$	0.035
3rd Layer	Al_2O_3	0.097
4th Layer	$ZrO_2 + TiO_2$	0.17
5th Layer	Al_2O_3	0.054
6th Layer	$ZrO_2 + TiO_2$	0.157
7th Layer	Al_2O_3	0.486
8th Layer	$ZrO_2 + TiO_2$	0.450
9th Layer	MgF_2	0.229

As is clear from FIG. **56**, the wavelength range of the anti-reflection coating **20**, in which the maximum reflectance was 0.2% or less, was as narrow as 280 nm (between 390 nm and 670 nm).

EXAMPLES 5-1 TO 5-8

In each anti-reflection coating **40** comprising first to seventh layers **41-47** on a substrate **30** according to the second embodiment of the present invention, the optimization of the refractive index and optical thickness of each layer for the refractive index of the substrate **30** was simulated, with air having a refractive index of 1.00 as an incident-side medium. The design wavelength was 550 nm. The refractive index of and optical thickness of each layer in Examples 5-1-5-8 are shown in Table 6. The spectral reflectance of each anti-reflection coating **40** of Examples 5-1 to 5-8 to perpendicular incident light was calculated by simulation, with the refractive index dispersion of the substrate **30** and the layers **41-47** taken into consideration, and with reflection on an opposite surface of the substrate **30** to the anti-reflection coating **40** neglected. The calculation results of reflectance are shown in FIGS. **57-64**.

TABLE 6

	Example 5-1		Example 5-2		Example 5-3	
Layer	Refractive Index	Optical Thickness (nm)	Refractive Index	Optical Thickness (nm)	Refractive Index	Optical Thickness (nm)
Substrate	1.4300	—	1.4700	—	1.5200	—
1st Layer	1.3800	266.45	1.4000	266.37	1.4000	266.33
2nd Layer	2.1015	43.04	2.2102	43.14	2.3235	43.50
3rd Layer	1.3801	41.11	1.4001	40.31	1.4318	40.33
4th Layer	2.2743	166.88	2.3701	166.80	2.5052	166.80
5th Layer	1.4607	15.33	1.4548	15.66	1.4521	15.91
6th Layer	2.2825	71.15	2.3375	71.58	2.4179	71.70
7th Layer	1.3800	133.57	1.3800	132.83	1.3800	132.36

	Example 5-4		Example 5-5		Example 5-6	
Layer	Refractive Index	Optical Thickness (nm)	Refractive Index	Optical Thickness (nm)	Refractive Index	Optical Thickness (nm)
Substrate	1.5700	—	1.6200	—	1.6700	—
1st Layer	1.4418	263.95	1.4829	260.93	1.5290	267.44
2nd Layer	2.2522	52.96	2.2139	62.25	2.5178	45.84
3rd Layer	1.4207	33.43	1.4794	29.40	1.5039	37.13
4th Layer	2.5651	165.88	2.6532	164.96	2.6393	157.23
5th Layer	1.4242	15.79	1.4791	16.11	1.4529	23.42
6th Layer	2.4424	72.59	2.4519	74.67	2.6487	61.57
7th Layer	1.3800	132.36	1.3800	131.27	1.3800	136.49

TABLE 6-continued

Layer	Example 5-7 Refractive Index	Example 5-7 Optical Thickness (nm)	Example 5-8 Refractive Index	Example 5-8 Optical Thickness (nm)
Substrate	1.7200	—	1.7300	—
1st Layer	1.5471	268.56	1.5471	269.44
2nd Layer	2.6040	47.81	2.6932	44.70
3rd Layer	1.4000	31.54	1.3800	31.80
4th Layer	2.6998	157.77	2.6998	160.04
5th Layer	1.4000	22.48	1.3800	21.68
6th Layer	2.6988	61.95	2.7000	61.94
7th Layer	1.3800	136.84	1.3800	136.69

As is clear from FIGS. **57-64**, the anti-reflection coatings **40** of Examples 5-1-5-8 had the maximum reflectance reduced to 0.2% or less in a wavelength bandwidth of 330 nm between 390 nm and 720 nm. This indicates that the anti-reflection coating of the present invention has sufficiently reduced reflectance in a wide wavelength range with a small number of lamination, thereby suppressing problems such as flare and ghost, which extremely deteriorate the optical characteristics, to obtain excellent color balance.

Referring to the results of Examples 5-1 to 5-8, anti-reflection coating materials having optimum refractive indices were selected for substrate materials actually used. The refractive index dispersion of each anti-reflection coating material is shown in FIG. **70**. Reflection-preventing characteristics obtained by using these substrate materials and anti-reflection coating materials were simulated in Examples and Comparative Examples below.

EXAMPLE 5-9

An anti-reflection coating **40** comprising first to seventh layers **41-47** made of the materials shown in Table 7 was formed on a substrate **30** of S-FSL5 (available from Ohara Inc., nd=1.4875) by a vapor deposition method. The spectral reflectance of the anti-reflection coating **40** to perpendicular incident light was calculated by simulation. The simulation results are shown in FIG. **65**.

TABLE 7

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-FSL5	1.4875	—
1st Layer	MgF_2	1.3880	251.19
2nd Layer	ZrO_2	1.9217	63.51
3rd Layer	MgF_2	1.3880	25.01
4th Layer	TiO_2	2.3132	203.05
5th Layer	SiO_2	1.4682	18.00
6th Layer	TiO_2	2.3132	38.62
7th Layer	MgF_2	1.3880	121.39

EXAMPLE 5-10

An anti-reflection coating **40** comprising first to seventh layers **41-47** made of the materials shown in Table 8 was formed on a substrate **30** of S-BSL7 (available from Ohara Inc., nd=1.5163) by a vapor deposition method. The spectral reflectance of the anti-reflection coating **40** to perpendicular incident light was calculated by simulation. The simulation results are shown in FIG. **66**.

TABLE 8

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-BSL7	1.5163	—
1st Layer	MgF_2	1.3880	257.31
2nd Layer	TiO_2	2.3132	32.23
3rd Layer	SiO_2	1.4682	43.54
4th Layer	TiO_2	2.3132	204.30
5th Layer	SiO_2	1.4682	16.34
6th Layer	TiO_2	2.3132	40.53
7th Layer	MgF_2	1.3880	122.61

EXAMPLE 5-11

An anti-reflection coating **40** comprising first to seventh layers **41-47** made of the materials shown in Table 9 was formed on a substrate **30** of S-BSM15 (available from Ohara Inc., nd=1.6230) by a vapor deposition method. The spectral reflectance of the anti-reflection coating **40** to perpendicular incident light was calculated by simulation. The simulation results are shown in FIG. **67**.

TABLE 9

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-BSM15	1.6230	—
1st Layer	SiO_2	1.4682	257.48
2nd Layer	TiO_2	2.3132	37.43
3rd Layer	SiO_2	1.4682	36.83
4th Layer	TiO_2	2.3132	170.03
5th Layer	SiO_2	1.4682	17.10
6th Layer	TiO_2	2.3132	55.25
7th Layer	MgF_2	1.3880	128.20

EXAMPLE 5-12

First to sixth layers **41-46** made of the materials shown in Table 10 was formed on a substrate **30** of S-LAL12 (available from Ohara Inc., nd=1.6779) by a sputtering method, and a seventh layer **47** made of the material shown in Table 10 was formed thereon by a vapor deposition method to obtain an anti-reflection coating **40**. The sputtered first layer **41** comprised 94% of TiO_2 and 6% of SiO_2. The spectral reflectance of the anti-reflection coating **40** to perpendicular incident light was calculated by simulation. The simulation results are shown in FIG. **68**.

TABLE 10

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-LAL12	1.6779	—
1st Layer*	$TiO_2 + SiO_2$	1.5399	263.94
2nd Layer*	TiO_2	2.4550	40.52
3rd Layer*	SiO_2	1.4815	36.16
4th Layer*	TiO_2	2.4550	157.29
5th Layer*	SiO_2	1.4815	20.57
6th Layer*	TiO_2	2.4550	61.02
7th Layer	MgF_2	1.3880	132.91

Note:
*Formed by a sputtering method.

COMPARATIVE EXAMPLE 2

An anti-reflection coating comprising first to ninth layers made of the materials shown in Table 11 was formed on a substrate of S-BSM15 (available from Ohara Inc., nd=1.6230) by a vapor deposition method. OH-5 in the anti-reflection coating is a depositing material comprising TiO_2 and ZrO_2, which is available from Canon Optron, Inc. The spectral reflectance of the anti-reflection coating to perpendicular incident light was calculated by simulation, with the refractive index dispersion of the substrate and the layers taken into consideration, and with reflection on an opposite surface of the substrate to the anti-reflection coating neglected. The simulation results are shown in FIG. **69**.

TABLE 11

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-BSM15	1.6230	—
1st Layer	Al_2O_3	1.6362	33.42
2nd Layer	OH-5	2.0422	34.15
3rd Layer	SiO_2	1.4682	36.90
4th Layer	OH-5	2.0422	142.03
5th Layer	SiO_2	1.4682	2.38
6th Layer	OH-5	2.0422	120.22
7th Layer	Al_2O_3	1.6362	202.95
8th Layer	SiO_2	1.4682	33.28
9th Layer	OH-5	2.0422	253.78
10th Layer	MgF_2	1.3880	125.34

The comparison of Examples 5-9 to 5-12 with Comparative Example 2 revealed that the anti-reflection coatings having the layer structures in Examples 5-9-5-12 have the maximum reflectance reduced to 0.2% or less in a wavelength bandwidth of 330 nm between 390 nm and 720 nm, while the anti-reflection coating having the layer structure in Comparative Example 2 has the maximum reflectance exceeding 0.2%.

As described above, the anti-reflection coating according to the second embodiment of the present invention has sufficiently reduced reflectance in a wide wavelength range with a small number of lamination, thereby suppressing problems such as flare and ghost, which extremely deteriorate the optical characteristics, to obtain excellent color balance.

EXAMPLES 6-1 TO 6-7

High-refractive-index layers **61**, **63**, **65**, **67**, **69**, **71** and **73** made of Nb_2O_5 having a refractive index of 2.312 to the d-line, and intermediate-refractive-index layers **62**, **64**, **66**, **68**, **70** and **72** made of a mixture of Nb_2O_5 and SiO_2 having a refractive index of 1.501 to the d-line were formed by a sputtering method, and a low-refractive-index layer **74** made of MgF_2 having a refractive index of 1.388 to the d-line was formed by a vapor deposition method, to form the anti-reflection coating **60** having the layer structure shown in FIG. **3** according to the third embodiment of the present invention on a substrate **50**. The substrates **50** used in Examples 6-1 to 6-7 were seven types of optical glass; S-FPL53 (available from Ohara Inc., nd=1.4388), S-BSL7 (available from Ohara Inc., nd=1.5163), S-BSM15 (available from Ohara Inc., nd=1.6230), S-LaL10 (available from Ohara Inc., nd=1.72000), S-LAH54 (available from Ohara Inc., nd=1.8155), S-NPH2 (available from Ohara Inc., nd=1.9229), and TAFD40 (available from HOYA Corporation, nd=2.0007), respectively.

With air having a refractive index of 1.00 as an incident-side medium, the optimum optical thickness of each layer **61-74** in each anti-reflection coating **60** was calculated by simulation. The optimum optical thickness of each layer is shown in Table 12.

TABLE 12

Layer		Optical Thickness (nm)			
		Example 6-1	Example 6-2	Example 6-3	Example 6-4
Substrate	—	S-FPL53	S-BSL7	S-BSM15	S-LAL10
1st Layer	Nb_2O_5	11.85	16.99	23.12	28.34
2nd Layer	$Nb_2O_5 + SiO_2$	86.65	71.56	56.50	45.40
3rd Layer	Nb_2O_5	55.02	61.80	71.66	81.18
4th Layer	$Nb_2O_5 + SiO_2$	28.64	25.88	21.32	16.77
5th Layer	Nb_2O_5	159.58	159.70	160.02	161.04
6th Layer	$Nb_2O_5 + SiO_2$	33.34	34.47	36.07	37.43
7th Layer	Nb_2O_5	46.64	45.80	44.39	42.85
8th Layer	$Nb_2O_5 + SiO_2$	165.88	167.35	168.31	169.51
9th Layer	Nb_2O_5	23.18	23.55	24.17	24.80
10th Layer	$Nb_2O_5 + SiO_2$	56.51	55.91	55.09	54.14
11th Layer	Nb_2O_5	154.66	154.36	155.64	156.15
12th Layer	$Nb_2O_5 + SiO_2$	14.76	15.00	15.09	15.38
13th Layer	Nb_2O_5	68.49	68.46	67.82	67.34
14th Layer	MgF_2	128.70	128.87	128.95	129.22

TABLE 12-continued

Layer		Optical Thickness (nm)		
		Example 6-5	Example 6-6	Example 6-7
Substrate	—	S-LAH54	S-NPH2	TAFD40
1st Layer	Nb_2O_5	33.13	35.89	41.85
2nd Layer	$Nb_2O_5 + SiO_2$	35.64	24.95	19.20
3rd Layer	Nb_2O_5	90.63	98.34	111.96
4th Layer	$Nb_2O_5 + SiO_2$	12.02	7.25	2.28
5th Layer	Nb_2O_5	162.89	165.05	172.52
6th Layer	$Nb_2O_5 + SiO_2$	38.63	39.65	40.77
7th Layer	Nb_2O_5	41.06	39.33	37.67
8th Layer	$Nb_2O_5 + SiO_2$	169.94	169.13	168.86
9th Layer	Nb_2O_5	25.36	26.11	26.93
10th Layer	$Nb_2O_5 + SiO_2$	53.15	52.41	51.69
11th Layer	Nb_2O_5	156.62	157.01	157.67
12th Layer	$Nb_2O_5 + SiO_2$	15.59	15.91	16.03
13th Layer	Nb_2O_5	66.88	66.32	66.24
14th Layer	MgF_2	129.17	129.30	129.78

The spectral reflectance of each anti-reflection coating **60** of Examples 6-1 to 6-7 to perpendicular incident light (incident angle=0°) was calculated by simulation, with the refractive index dispersion of the substrate **50** and the layers **61-74** of the anti-reflection coating **60** taken into consideration, and with reflection on an opposite surface of the substrate **50** to the anti-reflection coating **60** neglected. The calculation results are shown in FIGS. **71-76**. The refractive index dispersion of each material used in the anti-reflection coating **60** is shown in FIG. **87**.

EXAMPLES 7-1 TO 7-7

Anti-reflection coatings **60** were produced in the same manner as in Examples 6-1 to 6-7, except for changing the high-refractive-index material to TiO_2 having a refractive index of 2.455 and the intermediate-refractive-index material to Al_2O_3 having a refractive index of 1.644 as shown in Table 13. The optical thickness of each layer **61-74** was calculated by simulation in the same manner as in Examples 6-1 to 6-7. The spectral reflectance of each anti-reflection coating **60** of Examples 7-1 to 7-7 to perpendicular incident light (incident angle=0°) was calculated by simulation in the same manner as in Examples 6-1 to 6-7. The calculation results are shown in FIGS. **77-84**.

TABLE 13

Layer		Optical Thickness (nm)			
		Example 7-1	Example 7-2	Example 7-3	Example 7-4
Substrate	—	S-FPL53	S-BSL7	S-BSM15	S-LAL10
1st Layer	TiO_2	2.50	8.38	16.05	21.64
2nd Layer	Al_2O_3	122.58	98.85	75.56	61.36
3rd Layer	TiO_2	52.41	53.62	62.73	71.42
4th Layer	Al_2O_3	27.55	29.59	26.58	22.67
5th Layer	TiO_2	153.34	152.47	153.14	154.67
6th Layer	Al_2O_3	37.95	36.72	38.03	39.18
7th Layer	TiO_2	43.18	45.11	44.26	43.12
8th Layer	Al_2O_3	158.14	160.60	162.48	163.53
9th Layer	TiO_2	29.18	27.81	28.21	28.71
10th Layer	Al_2O_3	52.83	54.10	53.46	52.80
11th Layer	TiO_2	151.57	152.65	153.40	153.82
12th Layer	Al_2O_3	25.10	24.37	24.48	24.65
13th Layer	TiO_2	59.29	59.89	59.68	59.50
14th Layer	MgF_2	132.39	132.33	132.50	132.66

TABLE 13-continued

Layer		Optical Thickness (nm)		
		Example 7-5	Example 7-6	Example 7-7
Substrate	—	S-LAH54	S-NPH2	TAFD40
1st Layer	TiO_2	26.69	30.08	34.67
2nd Layer	Al_2O_3	50.15	38.27	31.90
3rd Layer	TiO_2	80.52	87.52	97.43
4th Layer	Al_2O_3	18.53	14.32	10.08
5th Layer	TiO_2	155.70	158.31	160.98
6th Layer	Al_2O_3	40.35	41.08	41.67
7th Layer	TiO_2	41.87	40.68	39.31
8th Layer	Al_2O_3	164.47	164.83	165.93
9th Layer	TiO_2	29.24	29.73	29.97
10th Layer	Al_2O_3	52.10	51.51	50.73
11th Layer	TiO_2	154.15	154.38	154.69
12th Layer	Al_2O_3	24.84	25.03	25.10
13th Layer	TiO_2	59.30	59.12	58.84
14th Layer	MgF_2	132.80	132.94	132.93

COMPARATIVE EXAMPLE 3

Referring to Embodiment 4 in JP 2000-111702 A, layers made of Ta_2O_5 having a refractive index of 2.233, and layers made of SiO_2 having a refractive index of 1.487 were alternately formed on a substrate made of S-BSL7, and a layer made of MgF_2 having a refractive index of 1.388 was formed thereon to form a 14-layer anti-reflection coating. The optimum optical thickness of each layer in this anti-reflection coating was calculated by simulation, with air having a refractive index of 1.00 as an incident-side medium. The results are shown in Table 14. The spectral reflectance of this anti-reflection coating to perpendicular incident light (incident angle=0°) was calculated by simulation in the same manner as in Examples 6-1 to 6-7. The calculation results are shown in FIG. **85**.

TABLE 14

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-BSL7	1.5163	—
1st Layer	Ta_2O_5	2.2330	19.18
2nd Layer	SiO_2	1.4870	58.93
3rd Layer	Ta_2O_5	2.2330	60.42
4th Layer	SiO_2	1.4870	22.31
5th Layer	Ta_2O_5	2.2330	131.16
6th Layer	SiO_2	1.4870	33.86

TABLE 14-continued

Layer	Material	Refractive Index	Optical Thickness (nm)
7th Layer	Ta_2O_5	2.2330	40.48
8th Layer	SiO_2	1.4870	171.20
9th Layer	Ta_2O_5	2.2330	19.12
10th Layer	SiO_2	1.4870	43.20
11th Layer	Ta_2O_5	2.2330	139.26
12th Layer	SiO_2	1.4870	9.86
13th Layer	Ta_2O_5	2.2330	72.12
14th Layer	MgF_2	1.3880	116.05

COMPARATIVE EXAMPLE 4

Referring to Embodiment 3 in JP 2002-14203 A, layers made of Ta_2O_5 having a refractive index of 2.233, layers made of TiO_2 having a refractive index of 2.455, and layers made of SiO_2 having a refractive index of 1.450 were formed on a substrate made of S-BSL7, to form a 14-layer anti-reflection coating. The optimum optical thickness of each layer in this anti-reflection coating was calculated by simulation, with air having a refractive index of 1.00 as an incident-side medium. The results are shown in Table 15. The spectral reflectance of this anti-reflection coating to perpendicular incident light (incident angle=0°) was calculated by simulation in the same manner as in Examples 6-1 to 6-7. The calculation results are shown in FIG. **86**.

TABLE 15

Layer	Material	Refractive Index	Optical Thickness (nm)
Substrate	S-BSL7	1.5163	—
1st Layer	TiO_2	2.4550	15.63
2nd Layer	SiO_2	1.4500	76.58
3rd Layer	TiO_2	2.4550	56.18
4th Layer	SiO_2	1.4500	36.73
5th Layer	TiO_2	2.4550	146.16
6th Layer	SiO_2	1.4500	21.16
7th Layer	Ta_2O_5	2.2330	83.59
8th Layer	SiO_2	1.4500	176.97
9th Layer	Ta_2O_5	2.2330	21.16
10th Layer	SiO_2	1.4500	60.83
11th Layer	TiO_2	2.4550	156.40
12th Layer	SiO_2	1.4500	5.95
13th Layer	TiO_2	2.4550	82.22
14th Layer	SiO_2	1.4500	127.65

The anti-reflection coatings according to the third embodiment of the present invention had reflectance of 0.1% or less in a wavelength bandwidth of 330 nm between 390 nm and 720 nm as shown in FIGS. **71-84**, while those of Comparative Examples 3 and 4 failed to achieve the target of reducing reflectance to 0.1% or less in a wavelength of 390 nm to 720 nm as shown in FIGS. **85** and **86**.

EFFECTS OF THE INVENTION

The anti-reflection coating of the present invention has not only low reflectance in a wide visible light band having a wavelength of 390 nm to 720 nm, but also extremely high transmission characteristics and excellent color balance. Accordingly, the use of such anti-reflection coating provides high-performance optical members and optical equipments free from problems such as flare and ghost, which extremely deteriorate the optical characteristics.

What is claimed is:

1. An anti-reflection coating comprising first to ninth layers laminated in this order on a substrate for having reflectance of 0.2% or less to light in a visible wavelength range of 390-720 nm,

said second, fourth, sixth and eighth layers being high-refractive-index layers each formed by a high-refractive-index material having a refractive index of 2.21-2.70 to a helium d-line having a wavelength of 587.56 nm;

said first, third, fifth and seventh layers being intermediate-refractive-index layers each formed by an intermediate-refractive-index material having a refractive index of 1.40 or more and less than 1.55 to said d-line; and

said ninth layer being a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.35 or more and less than 1.40 to said d-line;

wherein the refractive index difference between said intermediate-refractive-index layers and said high-refractive-index layers is 0.67-1.30.

2. The anti-reflection coating according to claim **1**, wherein said high-refractive-index material is TiO_2, Nb_2O_5, or a mixture or compound of at least two of TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZnO, ZrO_2, In_2O_3, SnO_2 and HfO_2; wherein said intermediate-refractive-index material is SiO_2, YbF_3, YF_3, or a mixture or compound of at least two of SiO_2, Al_2O_3, CeF_3, NdF_3, GdF_3, LaF_3, YbF_3 and YF_3; and wherein said low-refractive-index material is MgF_2, AlF_3, or a mixture or compound of at least two of MgF_2, AlF_3 and SiO_2.

3. The anti-reflection coating according to claim **1**, wherein said substrate has a refractive index of 1.40-2.10 to said d-line.

4. An optical member comprising the anti-reflection coating recited in claim **1**.

5. An optical equipment comprising the optical member recited in claim **4**.

6. A anti-reflection coating comprising first to seventh layers laminated in this order on an optical substrate with a refractive index of 1.43-1.73 to a helium d-line having a wavelength of 587.56 nm for having reflectance of 0.2% or less to light in a visible wavelength range of 390-720 nm,

said first layer having a refractive index of 1.37-1.56 to said d-line, and an optical thickness of 230-290 nm;

said second layer having a refractive index of 1.85-2.7 to said d-line, and an optical thickness of 20-80 nm;

said third layer having a refractive index of 1.37-1.52 to said d-line, and an optical thickness of 10-60 nm;

said fourth layer having a refractive index of 2.1-2.7 to said d-line, and an optical thickness of 130-220 nm;

said fifth layer having a refractive index of 1.37-1.52 to said d-line, and an optical thickness of 5-40 nm;

said sixth layer having a refractive index of 2.1-2.7 to said d-line, and an optical thickness of 20-90 nm; and

said seventh layer having a refractive index of 1.37-1.4 to said d-line, and an optical thickness of 100-160 nm.

7. The anti-reflection coating according to claim **6**, wherein said seventh layer has a refractive index equal to or less than those of said first, third and fifth layers.

8. The anti-reflection coating according to claim **6**, wherein said first, third and fifth layers are made of MgF_2 or SiO_2, or a mixture or compound of SiO_2 with Al_2O_3, Nb_2O_5 or TiO_2; wherein said second, fourth and sixth layers are made of TiO_2, Nb_2O_5, CeO_2, Ta_2O_5, ZrO_2, or any of their mixtures or compounds with SiO_2, and wherein said seventh layer is made of MgF_2, or a mixture or compound of MgF_2 with SiO_2, CaF_2 or LiF.

9. An optical member comprising the anti-reflection coating recited in claim **6**.

10. An optical equipment comprising the optical member recited in claim **9**.

11. A anti-reflection coating comprising first to fourteenth layers laminated in this order on an optical substrate having a refractive index of 1.43-2.01 to helium d-line having a wavelength of 587.56 nm,

said first, third, fifth, seventh, ninth, eleventh and thirteenth layers being high-refractive-index layers formed by high-refractive-index materials having refractive indices of 2.201-2.7 to said d-line;

said second, fourth, sixth, eighth, tenth and twelfth layers being intermediate-refractive-index layers formed by an intermediate-refractive-index material having a refractive index of 1.501-1.7 to said d-line;

said fourteenth layer being a low-refractive-index layer formed by a low-refractive-index material having a refractive index of 1.37-1.44 to said d-line;

said first layer having an optical thickness of 5-45 nm;

said second layer having an optical thickness of 15-125 nm;

said third layer having an optical thickness of 40-130 nm;

said fourth layer having an optical thickness of 1-45 nm;

said fifth layer having an optical thickness of 135-175 nm;

said sixth layer having an optical thickness of 20-50 nm;

said seventh layer having an optical thickness of 30-65 nm;

said eighth layer having an optical thickness of 155-180 nm;

said ninth layer having an optical thickness of 10-35 nm;

said tenth layer having an optical thickness of 45-75 nm;

said eleventh layer having an optical thickness of 147-170 nm;

said twelfth layer having an optical thickness of 5-28 nm;

said thirteenth layer having an optical thickness of 55-85 nm; and

said fourteenth layer having an optical thickness of 120-145 nm.

12. The anti-reflection coating according to claim **11**, wherein said optical substrate is made of optical glass, resins or optical crystals.

13. The anti-reflection coating according to claim **11**, wherein said high-refractive-index material is TiO_2 and/or Nb_2O_5; wherein said intermediate-refractive-index material is Al_2O_3, a mixture of SiO_2 with TiO_2, a mixture of SiO_2 with Nb_2O_5, a mixture of Al_2O_3 with TiO_2, or a mixture of Al_2O_3 with Nb_2O_5; and wherein said low-refractive-index material is MgF_2.

14. An optical member comprising the anti-reflection coating recited in claim **11**.

15. An optical equipment comprising the optical member recited in claim **14**.

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